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TITLE OF THESIS COMPARISON OF UPTAKE OF APPLIED AMMONIUM-

AND NITRATE-NITROGEN BY CROPS

DEGREE FOR WHICH THESIS WAS PRESENTED Master of Science

YEAR THIS DEGREE GRANTED Fall, 1973

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COMPARISON OF UPTAKE OF APPLIED AMMONIUM- AND NITRATE-NITROGEN BY CROPS

BY

© RICHARD HENRY LEITCH

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

Fall, 1973

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Comparison of Uptake of Applied Ammonium- and Nitrate-Nitrogen by Crops", submitted by Richard Henry Leitch, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The main objective of this work was to compare the effect of ammonium- and nitrate-based fertilizers on the yield, nitrogen uptake, and nitrate accumulation of different crops. Factors considered in comparing ammonium- and nitrate-based fertilizers were: time of application (fall and spring); method of application (mixing and band placement); and addition of a nitrification inhibitor, thiourea, to ammonium based fertilizers. Work consisted of: three greenhouse experiments with spinach (Spinacea oleracea), radish (Raphanus sativus),and barley (Hordeum vulgare) grown on three soils; and field experements with barley, turnip rape (Brassica campestris), and oats (Avena sativa) grown on three soils.

A greenhouse experiment with spinach and radish, grown on a soil which nitrified very slowly, showed that at very heavy rates of application ammonium-nitrogen depressed growth of the two crops more than did nitrate-nitrogen. However, application of nitrate produced extreme accumulation of nitrate-nitrogen in the tissue of both crops. Two other greenhouse experiments were concerned with inhibition of nitrification of applied $(NH_4)_2SO_4$ and urea. Placement of fertilizer in a band, rather than mixing throughout the soil, slowed nitrification of both $(NH_4)_2SO_4$ and urea. Addition of 20 or 25 ppm of thiourea to the banded fertilizer resulted in almost complete inhibition of nitrification of the fertilizers during the 5-week course of the greenhouse experiments. Further, thiourea at a rate of 20 or 25 ppm was not toxic to either

barley or radish.

In three field experiments, fall-applied $Ca(NO_3)_2$ was more subject than fall-applied $(NH_4)_2SO_4$ to immobilization early in the subsequent season, and also more subject to remineralization later in the season. Differences in the growth and nitrogen uptake of spring-sown field crops which had received fall applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ appeared to be the result of the different patterns of immobilization and remineralization of the two fertilizers. Early season growth and nitrogen uptake of rape was greater with fall-applied $(NH_4)_2SO_4$ than with fall-applied $Ca(NO_3)_2$ because of the greater immobilization in the spring of $Ca(NO_3)_2$ applied the previous fall. Fall and spring applications of $(NH_4)_2SO_4$ were equally effective in increasing the yield and nitrogen uptake of rapeseed, barley grain, and oat forage, whereas fall-applied $Ca(NO_3)_2$ was in most cases less efficient than spring-applied $Ca(NO_3)_2$.

Rape apparently preferred the nitrate form of nitrogen. Also indicated was a preference of rape for nitrogen fertilizers when placed in a band rather than when mixed in the soil.

Thiourea was found to be an effective nitrification inhibitor under field conditions when applied at a rate of 50-lb. per acre with banded $(NH_4)_2SO_4$ fertilizer, and at that rate was not toxic to barley, oats, or rape. Applications of thiourea modified the growth and nitrogen-uptake pattern of rape, and decreased the mid-season accumulation of nitrate-nitrogen in rape and oats.

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INTRODUCTION

Over the years researchers have conducted many experiments to compare ammonium and nitrate as sources of nitrogen for plant growth. In experiments with plants grown in nutrient solutions, some plant species have been found to grow better when fed with nitrate, and others when fed with ammonium. However, agricultural crops grown under field conditions have usually shown little difference in yield or quality when fertilized with nitrate-containing and ammonium-containing fertilizers. An explanation for this similarity of plant response under field conditions is probably that ammonium is nitrified quickly in most soils, and so crops feed largely on nitrate-nitrogen whether fertilized with nitrate-based or ammonium-based fertilizers.

Nitrification inhibitors, which slow the nitrification of ammonium, are now being added to ammonium-based fertilizers in some areas of the U.S.A. While nitrification inhibitors are not now used extensively, their use will probably increase because they substantially reduce leaching of fertilizer nitrogen by slowing the formation of nitrate which is very subject to leaching. Differences between ammonium-based and nitrate-based fertilizers may become apparent when applied ammonium is stabilized with an inhibitor, because ammonium and nitrate can behave quite differently in their reactions with soils and in their effect on plants. Specifically, ammonium is much less subject to both denitrification and leaching than is nitrate. On the other hand, ammonium may be more subject to immobilization by soil microorganisms. The two forms of nitrogen may also differ in their

effect on growth and uptake of nitrogen of some plant species. Finally, some food crops may accumulate high levels of nitrate in their tissues when they feed on nitrate, but not when they feed on ammonium.

Nitrification inhibitors will probably not come into common use in western Canada since leaching of nitrogen fertilizers is usually not a problem with the limited rainfall of the region. However, recent shifts in types of nitrogen fertilizers, and in their time of application may be of importance. There is increasing use of fertilizers which contain no nitrate (eg. anhydrous ammonia, and urea) and an increase in the amount of fertilizer applied in the fall rather than in the spring. Ammonium applied in the fall and stabilized with a nitrification inhibitor may remain as ammonium until spring and therefore undergo different reactions than if it had been nitrified.

The present study was undertaken with the general objective of comparing the effect of ammonium- and nitrate-based fertilizers on the yield and quality of crops. Specific objectives of the study were:

1. To compare ammonium- and nitrate-containing fertilizers when applied in the spring and when applied in the fall of the year.
2. To compare ammonium- and nitrate-containing fertilizers when mixed and when banded in the soil.
3. To study the accumulation of nitrate-nitrogen in plants fertilized with ammonium- and nitrate-nitrogen.
4. To determine the effectiveness of thiourea in inhibiting nitrification.

REVIEW OF LITERATURE

Nitrogen has long been recognized as an essential plant nutrient, and as the nutrient most often limiting crop yields. A large number of nitrogen fertilizers have been formulated to supplement the existing supply of nitrogen in soils. These fertilizers, which usually contain ammonium, or nitrate, or a mixture of the two, may affect the growth and quality of crops in different ways, and may also be immobilized at different rates by soil microorganisms. This review considers the effect of ammonium- and nitrate-nitrogen on the yield, nitrogen-uptake, and nitrate-nitrogen content of crops, and as well the immobilization of ammonium- and nitrate-nitrogen in soils. The effect of nitrification inhibitors in lessening losses of nitrogen fertilizer, and decreasing nitrate accumulation in crops is also reviewed. Particular emphasis is given to the nitrification inhibitor, thiourea.

Considerable controversy has arisen over the relative merits of ammonium- and nitrate-nitrogen for plant growth. Solution culture technique has been used extensively to study ammonium- and nitrate-nitrogen nutrition of plants (Arnon, 1937; Clark and Shive, 1934; Stahl and Shive, 1933a; and Stahl and Shive, 1933b). Using this method the possibility of nitrification is eliminated, but experimental conditions often tend to favour plant growth with nitrate as compared to ammonium. Use of unbuffered solutions, low cation: ammonium ratios, low light intensity, and low oxygen levels are listed as conditions associated with solution culture studies which are detrimental to plant uptake of

ammonium-nitrogen (Nightingale, 1948). Improved techniques, such as tracer studies with N^{15} and the use of nitrification inhibitors recently have come into use and have shown the importance of ammonium nutrition of plants (Huber and Watson, 1972; Spratt and Gasser, 1970). The increasing concern about losses of nitrates through leaching and denitrification, and concern about accumulation of toxic amounts of nitrates in plants grown for food or feed, may favour the use of ammonium- rather than nitrate-containing fertilizers in the future.

Most plants are capable of using both ammonium and nitrate forms of nitrogen (Nelson and Hauck, 1965; Muntz, 1893). Generally, nitrate-nitrogen is the form of nitrogen taken up by plants, not because plants prefer nitrate-nitrogen, but because ammonia is so rapidly oxidized in most soils (Alexander, 1967). Although nitrate-nitrogen is probably the most important source of nitrogen in agricultural soils it is not essential for plant growth, and under conditions which exclude the possibility of nitrification, normal plant growth can often be achieved with ammonium-nitrogen (Nightingale, 1937; Tam and Clark, 1943; Tam and Clark, 1945).

On nitrogen deficient soils the effect of fertilizer nitrogen is typically to increase the yield of plant material. At low rates of fertilizer addition, the increase in yield may exceed the increase in nitrogen uptake so that the per cent nitrogen in the plant falls. Beyond a certain limit however, the increase in yield no longer keeps pace with the increase in nitrogen uptake so that the per cent nitrogen in the plant rises (Russell, 1950). As pointed out by Terman *et al.*

(1969), an increase in protein content occurs only when nitrogen is absorbed in excess of the vegetative needs of the plant. This explanation is in keeping with the view that delayed nitrogen application results in increased protein production, because application of nitrogen after the vegetative needs of the plants have been met would represent a pool of unassimilated nitrogen which could go directly into protein synthesis. Although late applications of nitrogen have been found to increase the protein content of grains, the effect on yield of grain has generally been less encouraging with reports of no yield increase or reduced grain yields accompanying late spring applications of nitrogen (Borkowski and Kozera, 1956). Hucklesby et al. (1971) working with short, stiff-strawed wheats found that split applications of nitrogen resulted not only in higher protein content but also in higher yield of grain. They suggest that their results contradict the commonly held view that grain yields and grain protein content are negatively correlated, an opinion that had its origin in the use of varieties of grain susceptible to lodging.

To achieve maximum uptake of nitrogen by the plant it is important that sufficient nitrogen be available for plant needs throughout the growing season. The common practice of supplying nitrogen in a single dose at time of seeding is not consistent with this goal of maximizing nitrogen uptake. Rankin (1946) found that five separate applications of nitrogen were required to maximize total nitrogen uptake of spring wheat.

Form of applied nitrogen, whether ammonium- or nitrate-nitrogen, may also influences the seasonal uptake of nitrogen by plants. Gasser and Hamlyn (1968) found that wheat fertilized with $(NH_4)_2SO_4$ continued to take up nitrogen from flowering to harvest, whereas when fertilized with $Ca(NO_3)_2$ the wheat contained as much or more nitrogen at flowering than at harvest. Work by Hamid (1972) further supports the view that the seasonal uptake of ammonium- and nitrate-nitrogen differs. He found that three split applications of nitrate-nitrogen (seeding, tillering, bootstage) gave a significantly higher yield of wheat than a single application, while ammonium-nitrogen produced maximum yield when applied in two split applications (seeding, tillering).

A wide variety of factors influence plant preference for either ammonium- or nitrate-nitrogen. The pH of the nutrient medium exerts a considerable influence on the relative utilization of ammonium- and nitrate-nitrogen. Neutral or alkaline reaction favours ammonium uptake, while in acid media nitrate uptake is favoured (Clark and Shive, 1934; Nightingale, 1948). Spratt and Gasser (1970) have shown that soil moisture influences the relative effectiveness of ammonium- and nitrate-nitrogen in production of spring wheat. With adequate water, wheat produced the most dry matter (and grain) containing the most nitrogen when supplied with nitrate-nitrogen. However, when shortage of water limited growth, ammonium-nitrogen was as good or better than nitrate-nitrogen for increasing dry matter production and nitrogen uptake. Temperature also influences the relative uptake of ammonium- and nitrate-nitrogen. Frota and Tucker (1972) showed that nitrate-nitrogen

uptake by lettuce was influenced more by temperature than the absorption of ammonium-nitrogen, resulting in an increase in the ammonium to nitrate absorption ratio as the temperature decreased. The stage of plant growth also influences the relative uptake of ammonium- and nitrate-nitrogen. In the early stages of growth of wheat a preference for ammonium-nitrogen often occurs. Parr (1967) and Spratt and Gasser (1970) attribute this early-season preference for ammonium-nitrogen to the lack of a completely functional nitrate reductase enzyme system in young plants. Although a considerable amount of research has been directed towards proving that one form of nitrogen is superior to the other under a given set of conditions, it is often found that the best plant growth occurs when both ammonium- and nitrate-nitrogen are available (Naftel, 1930).

The application of higher rates of nitrogen in the production of agricultural crops has substantially widened the area of concern over nitrate accumulation in plants, because of the potential danger involved to humans and livestock from consumption of plants containing high levels of nitrate-nitrogen (Case, 1957; Morris, 1958). Actively growing plants can absorb nitrate-nitrogen against concentration gradients, which may result in the accumulation of nitrate-nitrogen within plants to levels several hundred times greater than that in the soil solution (Gul and Kolp, 1958). Nitrate-nitrogen within the plant represents a reserve of unassimilated nitrogen which is readily translocated within the plant from the roots and older tissues to the meristematic regions where demand for nitrogen is greatest (Nightingale, 1948). Experiments involving periodic sampling of plants throughout

the growing season have shown that nitrate-nitrogen content first rises and then after reaching a peak about the prebloom stage, declines as the plant matures (George et al., 1972; Gordon et al., 1962; Smith and Sund, 1965; and Streeter, 1972). When grain formation starts, the nitrogen subsequently absorbed from the soil and nitrogen from other plant parts enters into protein production of the grain (Russell, 1950).

Although authenticated instances of nitrate toxicity to livestock are increasing in number it is often the case that abnormal local conditions often are implicated in the diagnosis of nitrate poisonings. For example, the report by Mayo (1895) of cattle poisoning by nitrate was associated with a period of drought in Kansas. A great deal of research has been concerned with determining the factors which lead to the accumulation of nitrate-nitrogen in agricultural crops. Crawford et al.(1961) found that the factors which had a major influence on the concentration of nitrate-nitrogen in forages were: species, part of the plant, stage of maturity, light intensity, and level of nitrogen fertilization. Closely related species, varieties, kind of nitrogen fertilizer, and placement of nitrogen fertilizer were found to be secondary in importance to the level of nitrogen applied. Similarly, Baker and Tucker (1971) reported that rate of nitrogen fertilization and stage of maturity were important in the accumulation of nitrate-nitrogen in forages. They also found nitrate accumulation to be a function of the rate of phosphorous fertilization, a deficiency of phosphorous resulting in increased levels of nitrate-

nitrogen in forage. Griffith and Johnston (1960) and Griffith (1958) reported that the accumulation of nitrate-nitrogen in grasses varied both with the species and strain of grass. Similarly, Ryan et al. (1972) found wide variations in the level of nitrate-nitrogen in perennial forage grasses.

A great deal of controversy has arisen over the level of nitrate-nitrogen in plants which is toxic to livestock. Unfortunately, a single value cannot be given, but rather depends on a number of contributing factors such as the diet, rate of consumption, and weight of the animal. In 1940, Bradley et al. established the lower limit of a toxic hay at 0.20 per cent nitrate-nitrogen (oven-dry basis). Reduced rates of gain or milk production, depressed appetite, abortion, and other maladies of cattle have been attributed to diets containing sublethal concentrations of nitrate-nitrogen. Garner (1958) has set the maximum safe limit at 0.07 per cent nitrate-nitrogen if chronic or long term sublethal nitrate poisoning of cattle is to be avoided. Although findings reported in the literature are in general agreement with this range of 0.07 to 0.20 per cent nitrate-nitrogen, there are reports that higher levels are required for an animal to be fatally poisoned (Davison et al., 1964; Turner and Williams, 1970).

Unlike ammonium-nitrogen any nitrate-nitrogen taken up by the plant must be reduced prior to its use in new protein synthesis. That nitrate reduction and organic nitrogen synthesis may occur in the roots of plants, particularly perennials, is well known (Nightingale, 1937; Haas, 1937; Sanderson and Cocking, 1964a). Nitrate-nitrogen may also be reduced in the leaves of the plant by a light activated mechanism

closely linked with carbon dioxide reduction during photosynthesis (Hageman and Flesher, 1960; Sanderson and Cocking, 1964b). Engard (1939), working with raspberry, found that reduction of nitrate-nitrogen could occur not only in roots and leaves, but in all living cells of the plant. But nevertheless, the nitrate-reductase enzyme system may not reduce nitrate-nitrogen as quickly as it is taken up by the plant, therefore resulting in the accumulation of nitrate-nitrogen in plant tissue.

Nitrification inhibitors may be of practical value in the production of field crops for a number of reasons. Use of inhibitors with ammonium fertilizers may lessen losses of fertilizer nitrogen by leaching and denitrification, because ammonium-nitrogen leaches and denitrifies much less rapidly than nitrate. In addition, the accumulation of nitrate-nitrogen in crops could be reduced if a nitrification inhibitor was used to stabilize ammonium-nitrogen in the soil.

Thiourea, a sulfur containing organo-nitrogen compound, was one of the earliest reported inhibitors of nitrification. Using the soil perfusion technique, Quastel and Scholefield (1949) found that a concentration of 25 ppm of thiourea in the perfusion liquid inhibited nitrification for a period of 16 days. Subsequently (1951) they showed that nitrification was completely prevented for 21 days with a concentration of 380 ppm of thiourea. Jaques *et al*. (1959) using the soil perfusion technique, reported that 1.6×10^{-3} moles of thiourea per kilogram of soil (120 ppm thiourea) inhibited nitrification for about 20 days. McBeath (1962) found that exponential growth of

Nitrosomonas sp. and active nitrification could not occur until the concentration of thiourea in the perfusion liquid was reduced to less than 50 ppm. Using a direct determination of thiourea, McBeath also demonstrated that thiourea was readily decomposed in soil.

Thiourea was recognized by early workers to be a specific inhibitor of the microbial system oxidizing ammonia to hydroxylamine, but nevertheless the exact mode of action of thiourea was not clear. Lees (1946) and Quastel (1965) reported that the inhibitory effect of thiourea was caused by immobilization of copper ions required for nitrification. Quastel and Scholefield (1951) found this explanation unsatisfactory because of the apparent lack of toxicity of thiourea to biological oxidations in animal cells. Campbell and Alleem (1965) reported that while the action of N-Serve[2-chloro-6-(trichloromethyl) pyridine] was indeed on the copper component of the cytochrome oxidase system involved in ammonium oxidation, the action of thiourea appeared to be a blocking of ammonium transport to Nitrosomonas cells. While addition of copper (6×10^{-4} M Cu^{++}) completely reversed nitrification inhibition by N-Serve the same treatment was ineffective in reversing inhibition of nitrification by thiourea. McBeath (1962) noted that both N-Serve and thiourea inhibited nitrification by lengthening the lag period prior to exponential growth of Nitrosomonas sp. but N-Serve killed Nitrosomonas sp.,whereas thiourea did not.

Aside from its use as a nitrification inhibitor thiourea has also been studied as a source of nitrogen and sulfur for plant growth. After incubating 540 ppm of thiourea (containing 200 ppm N) for 90

days Fuller et al. (1950) recovered 154 ppm of ammonium-nitrogen, but no nitrate- or nitrite-nitrogen, showing that ammonium released from thiourea had not nitrified. They also showed that thiourea (50 lb/acre) gave a larger increase in yield of field-grown barley than did $(NH_4)_2SO_4$. Conrad (1940) investigated the retention of thiourea and other sulfur containing compounds by soils. He found that when 18 days of incubation occurred between addition of 120 ppm of thiourea and planting of green milo there was no evidence of toxicity of thiourea and a highly significant response to sulfur occurred. Hamlyn and Gasser (1967) studying the possible use of thiourea as a nitrogen fertilizer noted that high rates of thiourea mixed in the soil (1360 lb. thiourea per acre) inhibited nitrification of ammonia produced for up to 24 weeks. From their work they concluded that thiourea may be a practical source of nitrogen for crops with a long growing season, provided that the price of thiourea was not too high.

Use of a nitrification inhibitor, such as thiourea, may accentuate differences between ammonium-based and nitrate-based fertilizers by protecting applied ammonium from the rapid nitrification it undergoes in most soils. In some areas of the U.S.A. and Great Britain application of a nitrification inhibitor has been found to improve over-winter conservation of fall-applied ammonium (Gasser, 1965; Huber et al., 1969). Improved conservation with use of an inhibitor may be the result both of less leaching and less denitrification in the presence of ammonium as opposed to nitrate. Gasser and Hamlyn (1968) found that autumn-applied $(NH_4)_2SO_4$ increased early

season growth and nitrogen uptake of winter wheat before spring dressings were applied and that treating autumn-applied $(NH_4)_2SO_4$ with a nitrification inhibitor (N-Serve) increased growth and nitrogen uptake still further. Later growth and nitrogen uptake were increased more by spring dressings than by treated or untreated fertilizers applied in autumn.

In studying the nitrogen nutritional status of plants as related to disease control, Huber and Watson (1972) reported that stabilization of fall applied ammonium-nitrogen with N-Serve prevented nitrogen loss and eliminated the need for spring fertilization thereby reducing the severity of Cercosporella foot rot of winter wheat. Huber et al. (1969) found that treating fall-applied $(NH_4)_2SO_4$ with N-Serve reduced nitrification and increased the yield of winter wheat more than fall-applied $Ca(NO_3)_2$. Even without the use of a nitrification inhibitor Devine and Holmes (1964) found that autumn-applied $(NH_4)_2SO_4$ resulted in higher average yields of winter wheat than did $Ca(NO_3)_2$, but spring dressings of both fertilizers increased yields most. Although autumn applications of nitrogen have generally been found to be less effective than the equivalent spring applications, Widdowson et al.(1961) point out that for winter cereals it may be desirable to apply some nitrogen in autumn to avoid the low responses sometimes obtained when no nitrogen is applied until late spring.

Banding of ammonium-nitrogen either with the seed or beside the seed row has been shown to reduce the rate of nitrification.

Larsen and Kohnke (1946) found that when $(NH_4)_2SO_4$ was banded on the plow sole in autumn there was no appreciable nitrification during the winter months and no significant difference in yield of corn compared to spring applications of nitrogen. Gasser (1965) has also shown that band placement of $(NH_4)_2SO_4$ decreased nitrification and that addition of a nitrification inhibitor (N-Serve) enhanced this effect.

Pang et al. (1973) noted that the maximum rate of ammonium oxidation of band-applied ammonium fertilizers took place near the edges of the band, and that nitrification of the fertilizers was more rapid in alkaline than in acidic Manitoba soils. In studying the effect of banded nitrogen fertilizers on the growth of wheat roots, Passioura and Wetselaar (1972) found that the roots encompassed the fertilizer band in the case of urea, and thoroughly invaded it in the case of ammonium sulfate. From this work and from results of an earlier study, Wetselaar et al. (1972), they suggest that the efficiency of nitrogen use by wheat could be increased by banding nitrogen fertilizers because leaching of nitrate would be minimized.

It is generally believed that ammonium-nitrogen is immobilized more readily than nitrate-nitrogen by soil micro-organisms (Alexander, 1967; Jansson et al., 1955). For example, Jansson et al. (1955) showed that ammonium was utilized almost exclusively by microorganisms in the decomposition of oat straw when sufficient and equal quantities of ammonium- and nitrate-nitrogen were applied. Furthermore, Jansson (1958) has proposed that only a small part of soil organic matter is biologically active and that nitrate-nitrogen is outside the pathway

of the internal nitrogen cycle. This idea of a small active organic phase has been challenged by Broadbent (1966) on the basis that the remineralization of nitrogen freshly incorporated into the organic fraction proceeds at a very slow rate. The incorporation of some tagged nitrate-nitrogen into the organic fraction was also evidence that nitrate was not outside the pathway of the internal nitrogen cycle. Broadbent and Tyler (1962) have demonstrated that nitrate-nitrogen can be immobilized to a considerable extent when this was the only form of nitrogen available to soil microorganisms.

Tracer data presented by Broadbent (1962) have indicated that when tagged ammonium- or nitrate-nitrogen is added to soil there is almost immediately an increase in the mineralization of untagged nitrogen. In some cases the net release of nitrogen in the mineral form was found to exceed the quantity of nitrogen added. This stimulating effect of tagged fertilizer nitrogen on the release of untagged nitrogen was first reported by Broadbent and Norman (1946). Subsequent investigators (Bingeman et al., 1953) have referred to this phenomenon as a "priming effect". Broadbent (1966) found that addition of ammonium-nitrogen resulted in a greater "priming effect" than did nitrate-nitrogen. This is another difference between ammonium- and nitrate- containing fertilizers and an area in which the use of a nitrification inhibitor may be of importance.

Although a considerable amount of research has been concerned with comparing and contrasting ammonium-based and nitrate-based fertilizers in terms of plant uptake of nitrogen, yield of crops, and

fate of applied nitrogen in the soil, it is apparent that there are many areas of this subject that are not well understood. The complex nature of soil-nitrogen interactions makes investigation of any one facet of the nitrogen cycle a very difficult task. From the review of the literature it is evident that ammonium- and nitrate-nitrogen can affect the growth and quality of crops and transformations of nitrogen in the soil in quite different ways. Further understanding of these differences may be of value in increasing the efficiency of nitrogen used in the production of field crops.

METHODS AND MATERIALS

A. Greenhouse Experiments

Three pot culture experiments were conducted in the greenhouse. In these experiments the greenhouse temperature was allowed to vary between 18°C and 25°C, and a 16 hour photoperiod was maintained with a bank of fluorescent lamps which supplied a light intensity of approximately 1200 foot-candles at the upper plant leaf surface. All pots were randomly rearranged on the greenhouse bench each week and allowed to approach wilting before watering to field capacity by weight. At the termination of each greenhouse experiment plants were harvested by cutting 0.5 inch above the soil surface. Plant material was dried to constant weight in an oven at 65°C to determine the yield of dry matter. Soils used in the greenhouse experiments, which were analysed for content of NH_4^+-N and NO_3^--N at the end of each study, were air-dried and then passed through a 0.25-inch sieve prior to analyses.

1) The first pot culture experiment was conducted in the greenhouse to compare the growth and nitrate-nitrogen content of radish (*Raphanus sativus*) and spinach (*Spinacea oleracea*) when fertilized with ammonium- and nitrate-nitrogen. Radish and spinach were chosen because these plants are known to accumulate high concentrations of nitrate-nitrogen in their tissues (Barker *et al*., 1971; Brown and Smith, 1966). Spinach was grown in one series of the experiment and radish in a second series.

The soil used in this experiment was the 0 to 6 inch depth of a recently broken Luvisolic soil (Cold Stream series) which had grown a grain crop the previous year. This particular soil was known to nitrify slowly, and was chosen for that reason. Treatments included: $NaNO_3$ added at a rate of 0, 100, 200 and 400 ppm of nitrogen; and NH_4Cl added at a rate of 0, 100, 200 and 400 ppm of nitrogen. Each of these treatments was replicated twice, making a total of 32 pots in the experiment. Both NH_4Cl and $NaNO_3$ were applied in solution at the required concentration. Solutions of KH_2PO_4 and Na_2SO_4 were added to each pot to supply 50 ppm and 20 ppm of P and S, respectively. The fertilizer solutions were mixed with 1.4 kg. of soil and then each sample was placed in a sealed-bottom plastic pot which measured 5.5 inches in diameter.

Radish and spinach were thinned to 5 plants per pot after emergence. At the end of the experiment, 7 weeks after seeding, dry matter yield, and nitrate-nitrogen content of radish and spinach top growth and of radish roots were determined.

2) A second pot culture experiment was conducted in the greenhouse to determine the effect of band placement of $(NH_4)_2SO_4$ on nitrification and plant growth, and to determine whether addition of thiourea to the band of $(NH_4)_2SO_4$ would decrease nitrification without harming plant growth. The experiment consisted of one series of pots sown to radish (<u>Raphanus sativus</u>) and Galt barley (<u>Hordeum vulgare</u>), and a second series of pots left uncropped.

Two soils were used in this experiment: a Gleysolic soil from Calmar (Navarre Meadow); and a Luvisolic soil from Cooking Lake (Uncas series). A grain crop had been grown on both soils the previous year. The 0 to 6 inch depth of each soil was air-dried, passed through a 0.25-inch sieve, and mixed prior to potting. Main treatments were: no N (control); $(NH_4)_2SO_4$ mixed in the soil at a rate of 100 ppm of nitrogen; and $(NH_4)_2SO_4$ banded in the soil at a rate of 100 ppm of nitrogen. Sub-treatments consisted of various rates of thiourea added with $(NH_4)_2SO_4$ in the banded treatments. $(NH_4)_2SO_4$ was banded by placing the fertilizer in a straight row, approximately 0.5 inch long by 0.15 inch wide, in the centre of the pot at a depth of 1.5 inches below the soil surface. This method of band placement was used to ensure that the concentration of $(NH_4)_2SO_4$ in the band of the potted soil was equal to that which would occur in band placement of $(NH_4)_2SO_4$ in the field.

Four hundred grams of soil was placed in plastic pots which were 4.5 inches in diameter and had no drainage holes. Solutions of KH_2PO_4 and Na_2SO_4 were added to each pot to supply 40 and 20 ppm of P and S, respectively. Treatments were replicated 3 times for both the cropped and non-cropped series making a total of 42 pots in the experiment.

After emergence, barley was thinned to 4 plants per pot and radish thinned to 6 plants per pot. At the termination of the experiment, 5 weeks after seeding, the dry matter yield of barley and radish was determined, and soils of the non-cropped series were analyzed for content of ammonium- and nitrate-nitrogen.

3) A third greenhouse experiment was conducted to compare the effect of thiourea on nitrification of mixed and banded applications of $(NH_4)_2SO_4$ and urea. The experiment consisted of a non-cropped series and a second series to which Galt barley (Hordeum vulgare) was sown.

The 0 to 6 inch depth of a Gleysolic soil from Calmar (Navarre Meadow) was air-dried and passed through a 0.25-inch sieve prior to potting. The soil had grown a grain crop the previous year. Main treatments of the experiment included: urea mixed in the soil; urea banded in the soil; $(NH_4)_2SO_4$ mixed in the soil; $(NH_4)_2SO_4$ banded in the soil. These main treatments were split into a number of sub-treatments consisting of different rates of thiourea added with the urea and $(NH_4)_2SO_4$. In all treatments nitrogen, added either as $(NH_4)_2SO_4$ or urea, was applied at a rate of 100 ppm of nitrogen. Other nutrients added were P and S, at 40 and 20 ppm, respectively, as KH_2PO_4 and Na_2SO_4. All chemicals were added in solution with the exception of $(NH_4)_2SO_4$, urea, and thiourea, of the banded treatments, which were applied in granular form. The banded treatments consisted of fertilizers placed in a straight row 0.5 inch long by 0.15 inch wide in the center of the pot 1.5 inches below the soil surface. Each treatment was replicated three times making a total of 78 pots in the experiment.

The soil was placed in 5.5-inch diameter plastic pots of 1300 c.c. capacity which had no drainage holes. After emergence, barley was thinned to 8 plants per pot.

The experiment was conducted for five-week period from late

October to the end of November, 1972. Barley was thinned to 8 plants per pot after emergence. At the end of the experiment the dry matter yield of barley was determined, and the soils of the non-cropped series were analyzed for content of ammonium- and nitrate-nitrogen.

B. Field Experiments

Field experiments were placed at three sites: on a Chernozemic soil at Ellerslie (Malmo silty clay loam); on a Luvisolic soil at Vilna (La Corey sandy loam); and on a Gleysolic soil at Calmar (Navarre Meadow clay loam). The legal locations and soil descriptions are given in Appendix 1. The purpose of these experiments was to compare the effect of ammonium-nitrogen and nitrate-nitrogen on the yield and nitrogen uptake of Galt barley (*Hordeum vulgare*), Span rape (*Brassica campestris*), and Pendek oats (*Avena sativa*). At Ellerslie and Vilna,rape and oats were both grown and at Calmar,barley was grown. The field studies included a comparison of fall and spring applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ for spring sown crops. Banding of nitrogen fertilizers in the spring was also compared to the more conventional mixed application. Another facet of the field work included the use of the nitrification inhibitor, thiourea. Earlier work in the greenhouse had shown that thiourea was particularly effective in inhibiting nitrification when banded in the soil with $(NH_4)_2SO_4$ or urea.

1. Experimental Design and Treatments

Field experiments were set out in late October, 1971 in fields that had grown a grain crop in 1971. Main treatments included: no N (control); $(NH_4)_2SO_4$ mixed in the soil; $Ca(NO_3)_2$ mixed in the soil; $(NH_4)_2SO_4$ banded in the soil; $Ca(NO_3)_2$ banded in the soil; and $(NH_4)_2SO_4$ plus thiourea (50 lb. per acre) banded in the soil. In all cases nitrogen was applied at a rate of 100 pounds per acre, which included the nitrogen present in thiourea. The mixed applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ were applied in the autumn of 1971 and in the spring of 1972, but the banded applications were applied only in the spring. The banded treatments consisted of the fertilizers placed in a band 2 inches to the side and 0.5 inch below the seed row at time of seeding.

Individual treatments in the experiments were 6 feet wide and 24 feet long and replicated three times in a Randomized Complete Block design. Treatments were split into two parts, each 6 feet by 12 feet. One portion was cropped during 1972 and the other portion was not cropped but instead soil sampled periodically for analysis of ammonium-nitrogen and nitrate-nitrogen content. The cropped portion of treatments at Ellerslie and Vilna consisted of eight rows spaced 9 inch apart. Oats and rape were sown in each row to give equal 6-foot lengths of each crop.

At Calmar, the cropped area of each treatment contained 8 rows of barley, each 12 feet long. All crops were seeded with a single row hand-pushed seeder. Cropped portions of the experiments received

blanket applications of P, K, and S at 80, 50 and 20 pounds per acre, respectively. Fertilizer sources were treble superphosphate and K_2SO_4 which were broadcast and worked in prior to seeding.

2. Soil Sampling

In October, 1971 all sites were sampled to a depth of 3 feet, in 6-inch increments to a depth of 1 foot, and in 1-foot increments below, before any nitrogen was applied. Each soil sample was taken by combining five separate soil cores from each treatment. Fall-applied nitrogen treatments were soil sampled to a depth of 3 feet in May, 1972 prior to spring fertilizer application and seeding. Soil in the non-cropped portion of the experiments was subsequently sampled in late June and mid-July to a depth of 1 foot, and at harvest time to a depth of 3 feet. Soil samples were spread in the greenhouse to air-dry and then ground to pass a 2-mm sieve in preparation for analysis of ammonium- and nitrate-nitrogen content.

3. Plant Sampling and Harvesting

Plant samples of each crop were collected in late June and mid-July at the time that the soil samples were taken. These sampling dates corresponded with the end of tillering and the "boot stage" of growth of oats, respectively. At the late-June sampling period 20 plants were collected from each treatment and in mid-July 15 plants were taken. The mid-season plant samples were dried at 65°C, weighed, and passed through a 20-mesh sieve in preparation for analysis.

The final harvest sampling of crops was in early September. Oats was harvested as greenfeed, while rape and barley were allowed to ripen fully before harvesting. Two 4-foot rows of rape and oats, and two 8.25-foot rows of barley were harvested from unsampled center rows of each treatment. The samples were placed in cotton bags, dried at 65°C, and weighed. Rape and barley were threshed to determine seed yield. Representative samples of plant material including seed, straw, and forage, were passed through a 20-mesh sieve and placed in glass jars prior to analysis. Separate determinations of nitrate-nitrogen and total nitrogen were performed on all plant samples.

C. Laboratory Procedures

1. Extraction of Exchangeable Ammonium- and Nitrate-Nitrogen

Ammonium- and nitrate-nitrogen were extracted from soil and plant samples by shaking with 2 N KCl for 1 hour. For soil samples a 1:5 ratio of soil to 2N KCl was used and for plant samples 200 ml. of 2N KCl were added per gram of plant material.

2. Nitrogen Analysis

a) Inorganic Nitrogen in Soil and Plant Samples

Exchangeable ammonium-nitrogen and nitrate-nitrogen in soil and plant extracts were determined using the steam distillation method outlined by Bremner and Keeney (1966).

b) Total Nitrogen

Total nitrogen of plant samples was determined by the

semimicro-Kjeldahl method (Bremner, 1965), using a Parnas-Wagner (1921) micro-Kjeldahl steam distillation apparatus. A number of minor modifications were employed. Instead of distilling all of the digestion mixture, the digest was brought to a volume of 100 ml. and an aliquot steam distilled. With this modification only 10 ml. of 10N NaOH was required to make the digestion mixture sufficiently alkaline, and 0.005 N H_2SO_4 was used instead of 0.01 N H_2SO_4 in titration of the distillate.

3. Field Capacity

An estimate of field capacity for the soils used in the greenhouse experiments was made by placing 250 cc of soil into $1\frac{1}{2}$-inch diameter plastic cylinders and adding sufficient water to wet approximately 3/4 of the depth of soil in the cylinder. The tubes were covered but not sealed to minimize evaporation yet allow free drainage. After 48 hours the 1.5 - 2.5 inch depth of soil was sampled for moisture determination.

4. Routine Analyses

The mechanical analysis of soil samples was carried out by the hydrometer method (Bouyoucos, 1962). Soil pH values were determined with a glass electrode pH meter using a 1:2.5 soil-water suspension. Organic matter content was estimated using the Walkley-Black method as outlined by Allison (1965).

RESULTS AND DISCUSSION

A. Greenhouse Experiments

Effect of Ammonium- and Nitrate-Nitrogen on the Growth and Quality of Plants

Different nitrogen fertilizers have been found about equally effective in increasing plant growth at low rates of application. However, at high rates of application, plants often show a preference for one nitrogen fertilizer. This may occur because nitrogen is supplied in a form which is more readily used by the plant or because one nitrogen fertilizer is less toxic to the plant than another. Table 1 shows the results of a greenhouse experiment in which ammonium- and nitrate-containing fertilizers were applied to radish and spinach at rates of 0,100, 200, and 400 ppm of nitrogen. Generally, differences in plant growth between treatments receiving NH_4Cl and $NaNO_3$ were less at low rates of applied nitrogen than at high rates. Increasing the rate of application of NH_4Cl above 100 ppm of nitrogen resulted in a reduction in the dry matter yield of both spinach and radish tops. Growth of radish roots was also depressed at rates of NH_4Cl above 100 ppm of nitrogen. However, when fertilized with $NaNO_3$ there was not a significant reduction in the growth of spinach or of radish roots at the 200 ppm rate of applied nitrogen. Top growth of radish was not significantly depressed even at the highest rate of $NaNO_3$ (400 ppm of nitrogen). At all three rates of applied nitrogen the growth of spinach and both root and top growth of radish were greater

Table 1. Dry matter yield of spinach and radish grown with different rates of ammonium- and nitrate-nitrogen in a greenhouse pot experiment.

Fertilizer	Rate of N (ppm)	Yield of dry matter (g/pot)[1]		
		Spinach	Radish (top growth)	Radish (root)
NH_4Cl	0	0.93b*	0.76b	1.07b
	100	1.50cd	1.58c	1.02b
	200	1.01b	0.58b	0.10a
	400	0.23a	0.09a	0a
$NaNO_3$	0	0.93b	0.76b	1.07b
	100	1.98e	2.28d	2.16c
	200	1.67de	2.79e	1.88c
	400	1.23bc	2.70e	0.95b

1 Average of 2 replicates

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

with $NaNO_3$ than with NH_4Cl. Spinach and radish top growth and radish root growth were significantly lower on the treatment which received 400 ppm of nitrogen as NH_4Cl than on the control treatment. However, there was not a reduction in growth of radish or spinach as compared to the control treatment when 400 ppm of nitrogen was applied as $NaNO_3$. Top growth of radish was even greater on the treatment which received the highest rate of $NaNO_3$ than on the control treatment.

Accompanying the greater growth of spinach and radish with $NaNO_3$ than with NH_4Cl was a greater accumulation of nitrate-nitrogen in plants fertilized with $NaNO_3$ (Table 2). When 100 ppm of nitrogen was applied as $NaNO_3$ spinach accumulated 14,800 ppm of nitrate-nitrogen, whereas at the equivalent rate of application of NH_4Cl there was only 900 ppm of nitrate-nitrogen in spinach. At the 400 ppm rate of application of nitrogen, spinach accumulated 850 ppm of nitrate-nitrogen when fertilized with NH_4Cl and 23,400 ppm when $NaNO_3$ was applied. Radish roots contained similar concentrations of nitrate-nitrogen at the 100 ppm rate of nitrogen, whether $NaNO_3$ or NH_4Cl was applied. The concentration of nitrate-nitrogen in radish tops and roots did not increase at rates of NH_4Cl above 100 ppm of nitrogen, however when $NaNO_3$ was applied there was a noticeable increase in the accumulation of nitrate-nitrogen in radish roots and in the top growth of radish as the level of applied nitrogen was increased. At the highest rate of $NaNO_3$ (400 ppm of nitrogen) the top growth of radish contained 31,000 ppm of nitrate-nitrogen. Despite this extremely high concentration of nitrate-nitrogen in the radish tissue

Table 2. Nitrate-nitrogen content of spinach and radish grown with different rates of ammonium- and nitrate-nitrogen in a greenhouse pot experiment.

		NO_3^--N content (ppm)[1,2]		
Fertilizer	Rate of N (ppm)	Spinach	Radish (top growth)	Radish (root)
NH_4Cl	0	90	138	120
	100	901	1,440	4,140
	200	701	817	4,070
	400	859	710	--
$NaNO_3$	0	107	142	138
	100	14,800	7,120	5,760
	200	15,300	22,600	12,700
	400	23,400	31,200	18,500

1 Nitrate-nitrogen content expressed on an oven-dry basis

2 Average of 2 replicates

there was no evidence of growth depression on this treatment.

This greenhouse experiment demonstrated a clear difference in plant response to ammonium- and nitrate-nitrogen. Plants showed a preference for nitrate-nitrogen at all rates of nitrogen application. This is in contrast to results of field experiments in which little or no difference has been found in the yield of crops at low rates of application of ammonium- and nitrate-containing fertilizers (Power et al., 1972). Solution culture studies have, however, shown that ammonium depresses plant growth more than nitrate at high concentrations of nitrogen (Clark, 1936). In the present experiment, the greater plant growth with $NaNO_3$ than with NH_4Cl at the low rate of application (100 ppm N) is of particular interest, because this rate of nitrogen (approximately equivalent to 200 lb. per acre of N) is only slightly greater than commonly used field rates and therefore implies that form of applied nitrogen might well be an important factor in field crop production.

Another important difference between plants fertilized with ammonium- and nitrate-nitrogen was the greater accumulation of nitrate-nitrogen in plants which received $NaNO_3$. In contrast, Griffith and Johnston (1960) found that the form of applied nitrogen, whether ammonium- or nitrate-nitrogen, made little difference in the nitrate accumulation of rape. Crawford, et al. (1961) and Barker et al. (1971) also reported that form of applied nitrogen was not an important factor in nitrate accumulation in plants. Nyborg (personal communication) found that the soil used in the present greenhouse

experiment nitrified added ammonium-nitrogen very slowly (approximately 10 ppm of ammonium nitrified in 4 weeks). Any differences in nitrate accumulation or plant growth from form of applied nitrogen would be more pronounced in such a slowly nitrifying soil than in other more rapidly nitrifying soils.

The levels of nitrate-nitrogen which accumulated in spinach fertilized with $NaNO_3$ were greater than levels commonly reported in the literature. For example, Barker et al. (1971) found that spinach contained 0.67 per cent nitrate-nitrogen when fertilized with NH_4NO_3 at a rate of 200 ppm of nitrogen. Brown and Smith (1966) reported that radish accumulated the most nitrate-nitrogen of eight vegetable varieties tested. They found that radish contained 2.0 per cent nitrate-nitrogen when fertilized with 400 pounds per acre of NH_4NO_3 (approximately 200 ppm N), which is similar to the level of nitrate-nitrogen which accumulated in radish in the present greenhouse experiment. Consumption of plants containing such high levels of nitrate-nitrogen could be fatal to humans and in particular to infants. In Germany, a number of cases of nitrate poisoning of infants have been reported from consumption of spinach containing high levels of nitrate-nitrogen (Simon, 1966). Indications are that there is little risk of nitrate poisoning of adult humans from consumption of high nitrate-containing leafy vegetables, but nevertheless continued attention should be given to the nitrate content of vegetables especially in relation to fertilization practices.

Inhibition of Nitrification of $(NH_4)_2SO_4$ Through Band Placement and Addition of Thiourea

In order to compare plant growth with ammonium- and nitrate-nitrogen in soils some means must be found to inhibit the rapid nitrification which normally occurs when ammonium-nitrogen is added to the soil. Two methods which have been used to retard nitrification are: band placement of the ammonium fertilizer in the soil; and the use of a nitrification inhibitor. When the nitrification inhibitor is added to the band of ammonium fertilizer an even greater degree of control over nitrification should be possible.

The effect on nitrification of banding $(NH_4)_2SO_4$ and adding thiourea to the band of $(NH_4)_2SO_4$ in two non-cropped soils is shown in Table 3. After the 5 week incubation period approximately 90 per cent of the mixed application of $(NH_4)_2SO_4$ had been nitrified in the Gleysolic soil while 78 per cent nitrification had occurred in the Luvisolic soil (per cent nitrification was calculated as per cent of applied nitrogen not recovered as exchangeable ammonium). Band placement of $(NH_4)_2SO_4$ significantly reduced the rate of nitrification compared to the mixed application of $(NH_4)_2SO_4$ on both soils. Addition of 5 ppm or 25 ppm of thiourea to the band of $(NH_4)_2SO_4$ had little effect in inhibiting nitrification beyond that of band-applied $(NH_4)_2SO_4$. However, addition of 125 ppm of thiourea to the band of $(NH_4)_2SO_4$ significantly reduced nitrification on both soils as compared to the banded application of $(NH_4)_2SO_4$. The control over nitrification which is possible through addition of thiourea to the band of $(NH_4)_2SO_4$

Table 3. Effect of band placement and addition of thiourea on nitrification of $(NH_4)_2SO_4$ and dry matter yield of barley and radish on two soils under greenhouse conditions.

Treatment	Method of Application	Mineral - N remaining in non-cropped soil after 5 weeks (ppm)[1]				Yield of dry matter (g/pot)			
		Gleysolic soil		Luvisolic soil		Barley		Radish	
		NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	Gleysolic soil	Luvisolic soil	Gleysolic soil	Luvisolic soil
Control	--	--	--	--	--	0.11b	0.13a	0.22b	0.31bc
$(NH_4)_2SO_4$	mixed	12a*	48	22a	46	0.29de	0.27bc	0.49c	0.69e
$(NH_4)_2SO_4$	banded	43b	12	62b	12	0.31e	0.39d	0.34b	0.67de
$(NH_4)_2SO_4$ + 5 ppm thiourea	banded	49b	12	62b	16	0.24cde	0.42d	0.33b	0.54de
$(NH_4)_2SO_4$ + 25 ppm thiourea	banded	50b	4	70bcd	6	0.25cde	0.32c	0.33b	0.48cd
$(NH_4)_2SO_4$ + 125 ppm thiourea	banded	68c	0	89cde	0	0.19c	0.24b	0.21b	0.27ab
$(NH_4)_2SO_4$ + 600 ppm thiourea	banded	88c	6	109e	8	0.05a	0.08a	0a	0.10a

[1] Net amount: NH_4^+-N (4 ppm) and NO_3^--N (16 ppm) in control treatment has been deducted.

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

NOTE: For all treatments $(NH_4)_2SO_4$ applied at a rate of 100 ppm of nitrogen.

was evident at the highest rate of application of thiourea. Addition of 600 ppm of thiourea to the band of $(NH_4)_2SO_4$ completely inhibited nitrification for 5 weeks in the Luvisolic soil, and on this treatment only 12 per cent of the added ammonium was nitrified in the Gleysolic soil.

Plant response to banding of ammonium fertilizers and addition of thiourea will depend on plant preference for ammonium-nitrogen or nitrate-nitrogen, preference for banded nitrogen or mixed nitrogen, and the phytotoxicity of thiourea. The effect of band placement of $(NH_4)_2SO_4$ and addition of thiourea on the growth of barley and radish tops is shown in Table 3. Banding of $(NH_4)_2SO_4$ depressed the dry-matter yield of radish on the Gleysolic soil, however on the Luvisolic soil there was little difference in the growth of radish when $(NH_4)_2SO_4$ was banded and when mixed in the soil. Growth of barley was also similar on banded and mixed applications of $(NH_4)_2SO_4$ on the Gleysolic soil, while on the Luvisolic soil the dry matter yield of barley was greater with band-applied $(NH_4)_2SO_4$ than with the mixed applications of $(NH_4)_2SO_4$.

Rates of thiourea up to 25 ppm did not significantly depress the dry matter yield of radish or barley on the Gleysolic soil nor the yield of radish on the Luvisolic soil as compared to band-applied $(NH_4)_2SO_4$. When 125 ppm of thiourea was added to the band of $(NH_4)_2SO_4$ barley growth was less than on the band applied $(NH_4)_2SO_4$ treatment, but still greater than on the control treatment. However, on both soils the dry matter yield of radish on the treatment which received 125

ppm of thiourea was not significantly different from the control treatment. At the 600 ppm rate of thiourea both radish and barley growth was seriously depressed.

The results of this greenhouse experiment showed that the rate of nitrification of $(NH_4)_2SO_4$ could be reduced through band placement of the fertilizer in the soil. The lower nitrification of banded than of mixed applications of $(NH_4)_2SO_4$ has also been demonstrated by other workers (Larsen and Kohnke, 1946; Gasser, 1965). Except for radish grown on the Gleysolic soil, the growth of radish and barley was similar when $(NH_4)_2SO_4$ was banded and when mixed in the soil. This is not in agreement with work of Gasser (1965) who found that growth of ryegrass was better with mixed than with banded $(NH_4)_2SO_4$.

Addition of 125 ppm of thiourea to the band of $(NH_4)_2SO_4$ was found to reduce the rate of nitrification of band-applied $(NH_4)_2SO_4$. Rates of thiourea greater than 125 ppm have generally been reported necessary to inhibit nitrification of $(NH_4)_2SO_4$. For example, Hamlyn and Gasser (1967) found that 1360 lb. per acre of thiourea (roughly equivalent to 680 ppm) was required to inhibit nitrification when mixed in the soil. In the present experiment addition of 125 ppm of thiourea to the band of $(NH_4)_2SO_4$ depressed the growth of radish and spinach. To the author's knowledge there have been no other reports dealing with the range of toxicity of thiourea to plants when banded with $(NH_4)_2SO_4$ in the soil. However, Beaton et al. (1967) have reported that growth of orchardgrass was depressed when 320 ppm of thiourea was mixed in the soil. The results of this greenhouse experiment provided information regarding the nitrification of $(NH_4)_2SO_4$ which was useful

in selecting treatments to be used in subsequent field and greenhouse experiments.

Inhibition of Nitrification of Urea Through Band Placement and Addition of Thiourea

The use of urea in the production of field crops is presently increasing, and urea will probably be one of the major sources of fertilizer nitrogen in the future. When urea is added to the soil it is rapidly hydrolyzed to ammonium which is subsequently oxidized by soil microorganisms to nitrate-nitrogen. The preceding greenhouse experiment indicated that band placement of $(NH_4)_2SO_4$ reduced the rate of nitrification of this fertilizer and that addition of thiourea to the band of $(NH_4)_2SO_4$ enhanced this effect. It was of interest then to determine if these methods of inhibiting nitrification would be effective in reducing the rate of nitrification on ammonium formed on hydrolysis of urea.

A pot culture experiment was set up consisting of two series: one set of potted soils was sown to Galt barley (*Hordeum vulgare*);and a second series was not cropped but instead analyzed for ammonium- and nitrate-nitrogen content at the end of the experiment. The results of this greenhouse experiment are shown in Table 4. When urea and $(NH_4)_2SO_4$ were mixed in the soil there was almost complete nitrification of both fertilizers after 5 weeks. When applied in a band however, only 50 per cent of $(NH_4)_2SO_4$ was nitrified and approximately 80 per cent of band-applied urea was nitrified (per cent nitrification was calculated as per cent of applied nitrogen not recovered as exchangeable ammonium).

Table 4. Effect of band placement and addition of thiourea on nitrification of $(NH_4)_2SO_4$ and urea and dry matter yield of barley on a Gleysolic soil in the greenhouse.

Treatment	Method of Application	Mineral-N remaining in non-cropped soil after 5 weeks (ppm)[1] NH_4^+-N	NO_3^--N	Yield of dry matter (g/pot)
Control	--	--	--	0.64ab
Urea	mixed	2a*	70	1.19e
$(NH_4)_2SO_4$	mixed	5ab	58	1.11de
Urea	banded	22abcd	50	0.77ab
$(NH_4)_2SO_4$	banded	47de	25	0.95cd
Urea + 10 ppm thiourea	banded	51ef	15	0.79bc
Urea + 20 ppm thiourea	banded	56ef	7	0.79bc
Urea + 40 ppm thiourea	banded	65efg	1	0.60a
$(NH_4)_2SO_4$ + 40 ppm thiourea	banded	63efg	6	0.67ab
Urea + 10 ppm thiourea	mixed	7abc	70	1.19e
Urea + 20 ppm thiourea	mixed	5ab	72	1.17e
Urea + 40 ppm thiourea	mixed	8abc	72	1.03de
$(NH_4)_2SO_4$ + 40 ppm thiourea	mixed	13abc	59	1.09de

[1] Net amount: NH_4^+-N (2 ppm) and NO_3^--N (29 ppm) in control treatment has been deducted.

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

NOTE: For all treatments $(NH_4)_2SO_4$ and urea applied at a rate of 100 ppm of N.

Addition of only 10 ppm of thiourea to the band of urea resulted in recovery of ammonium-nitrogen equal to that of band-applied $(NH_4)_2SO_4$. Higher rates of thiourea included in the band of urea inhibited nitrification of urea slightly more than the 10 ppm rate of thiourea. When 40 ppm of thiourea was added to band-applied $(NH_4)_2SO_4$ and to band-applied urea, approximately 65 per cent of the applied nitrogen of both fertilizers had not been nitrified after 5 weeks. Thiourea was ineffective in inhibiting the nitrification of mixed applications of $(NH_4)_2SO_4$ and urea. Even when 40 ppm of thiourea was applied there was not a significant reduction in the nitrification of either fertilizer.

Growth of barley was similar on treatments which received mixed applications of $(NH_4)_2SO_4$ and urea, and addition of thiourea to these treatments did not depress barley growth. As well, yield of barley was not significantly reduced by addition of thiourea to the band of urea, even at the highest rate of application (40 ppm). However, 40 ppm of thiourea added to the band of $(NH_4)_2SO_4$ resulted in a lower yield of barley than on the band- applied $(NH_4)_2SO_4$ treatment which received no thiourea. Dry matter yield of barley was greater on the treatment in which $(NH_4)_2SO_4$ was banded than on the band-applied urea treatment.

This greenhouse experiment provided additional information regarding the nitrification of $(NH_4)_2SO_4$ and showed that thiourea was effective in reducing the nitrification of urea when banded in the soil. Of particular interest was the decrease in the rate of nitrification when only 10 ppm of thiourea was added to the band of urea. This

concentration of thiourea is much lower than levels which have previously been reported necessary to control nitrification (Hamlyn and Gasser, 1967). In this experiment there was no benefit to plant growth when the rate of nitrification was reduced through the use of thiourea. However, under field conditions increased crop yields would be expected from addition of thiourea, because less nitrogen would be present in the nitrate form which is more readily lost through leaching than is ammonium-nitrogen. This experiment showed that thiourea was much less efficient in reducing the rate of nitrification of urea when mixed in the soil than when banded with urea. The high concentration of thiourea required to inhibit nitrification when mixed in the soil has been a major factor limiting the use of this compound. This has occurred because at these high rates of application thiourea has been found to be toxic to plants (Fuller _et al_., 1950). The results of this greenhouse experiment indicate that this problem can be circumvented by placing thiourea in direct contact with urea in the soil.

B. Field Experiments

Often there is little difference in the yield and quality of field crops which receive ammonium-based and nitrate-based fertilizers (Power et al., 1972). However, applied ammonium is usually oxidized rapidly to nitrate in soils, and consequently crops fertilized with ammonium-nitrogen may nevertheless feed largely on nitrate. When applied ammonium nitrifies slowly (as with the use of an effective nitrification inhibitor) differences between ammonium-based and nitrate-based fertilizers may then become apparent.

The greenhouse experiments had shown that band placement and use of thiourea reduced the rate of nitrification of both urea and ammonium sulphate. The greenhouse experiments also showed that plants grew better with nitrate, but concomitantly accumulated very high levels of nitrate in their tissue. At the same time, high rates of thiourea were toxic to plants in the greenhouse. Consequently, field experiments were undertaken at three sites to find if thiourea was an effective nitrification inhibitor under field conditions, and also to find the effect of a nitrification inhibitor on the yield and quality of several crops in the field. The field experiments were concerned, as well, with a comparison of fall and spring applications of ammonium-based and nitrate-based fertilizers, with the hypothesis that ammonium would over-winter better than nitrate because ammonium is less subject to leaching and denitrification.

The three field experiments consisted of non-cropped portions used for periodic soil sampling to determine amounts of ammonium- and nitrate-nitrogen in different treatments, and consisted as well of cropped portions used in periodic sampling of crops for determination of yield and nitrogen content.

Recovery of Nitrogen Fertilizers in Non-Cropped Soil

In western Canada, fall-applied nitrogen fertilizers may over-winter well because of little leaching or denitrification during the winter season when the soil is deeply frozen. Little difference may be expected in the recovery in spring of ammonium- and nitrate-

containing fertilizers if applied early enough in the fall for nitrification of ammonium-nitrogen to occur. However, if fertilizers were applied late in the fall just before freeze-up, some differences in recovery between ammonium- and nitrate-containing fertilizers might then occur.

Table 5 shows the recovery of mineral nitrogen in late May, 1972 from $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ applied in late October, 1971. At the Calmar site there was little difference in the recovery of nitrogen in late May from fall applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$. At the Ellerslie and Vilna sites over 90 per cent of the nitrogen applied the previous fall as $(NH_4)_2SO_4$ was recovered the following spring. Recovery of fall-applied $Ca(NO_3)_2$ at the Vilna site was slightly less than recovery of $(NH_4)_2SO_4$. At Ellerslie, only 48 per cent of fall-applied $Ca(NO_3)_2$ was recovered the following spring as compared to 95 per cent recovery of fall-applied $(NH_4)_2SO_4$.

Treatments receiving the fall-applied fertilizers were sampled four months later, in September (Table 5). At the Ellerslie site, recovery of nitrogen from fall-applied $(NH_4)_2SO_4$ increased from 95 per cent in May to 135 per cent in September, while recovery of fall-applied $Ca(NO_3)_2$ increased from 48 per cent in May to 146 per cent in September.

At the Vilna site there was little change in the recovery of the fall-applied nitrogen fertilizers during the summer months. Recovery of nitrogen in the Gleysolic soil at Calmar demonstrated quite a different pattern than at Ellerslie and Vilna. While recovery of nitrogen from fall-applied $(NH_4)_2SO_4$ dropped from 77 per cent in

Table 5. Recovery in non-cropped soil in May of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ applied the previous fall.

	Apparent per cent of fertilizer - N recovered in top 36 inches of soil[1]		
Fertilizer	Ellerslie	Calmar	Vilna
*$(NH_4)_2SO_4$	95b[+]	77a	92a
*$Ca(NO_3)_2$	48a	85a	74a

* Both fertilizers applied at a rate of 100 lb. N/acre.

[+] For each column values are significantly different (95% level of probability) when not followed by the same letter.

[1] Net amount: NH_4^+- and NO_3^--N content of control treatment has been subtracted.

Table 6. Recovery in non-cropped soil in September of fall and spring applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$.

		Apparent per cent of fertilizer -N recovered in Sept., 1972 in top 36 inches of soil[1]		
Time of fertilizer application	Fertilizer	Ellerslie	Calmar	Vilna
October, 1971	*$(NH_4)_2SO_4$	135	32	113
	*$Ca(NO_3)_2$	146	66	77
May, 1972	*$(NH_4)_2SO_4$	124	45	62
	*$Ca(NO_3)_2$	184	94	136

* Fertilizers applied at a rate of 100 lb. N per acre.

[1] Net amount: NH_4^+- and NO_3^--N content of control has been subtracted.

May to 32 per cent in September, the recovery of $Ca(NO_3)_2$ decreased only from 85 per cent in May to 66 per cent in September.

The lower recovery of nitrogen in the spring from fall-applied $Ca(NO_3)_2$ than from fall-applied $(NH_4)_2SO_4$ at the Ellerslie site cannot be explained as leaching or denitrification of the nitrate, because by September the $Ca(NO_3)_2$ treatment contained more mineral nitrogen than the $(NH_4)_2SO_4$ treatment. Instead the $Ca(NO_3)_2$ must have been immobilized more than was $(NH_4)_2SO_4$. This stands quite contrary to the conventional view that ammonium is more rapidly immobilized than is nitrate-nitrogen (Janssan, 1955). Fall-applied $Ca(NO_3)_2$ also undergoes more intensive remineralization than fall-applied ammonium, because more than 100 per cent of the applied nitrate was apparently recovered by fall. The changes with time in mineral nitrogen recovery at the Ellerslie site were larger than those at the Vilna and Calmar sites.

The immobilization and remineralization of fall-applied fertilizers during the summer months at the three field sites is shown in Figures 1, 2, and 3, (values in the three figures were calculated as content of NH_4^+- plus NO_3^--N in the top 12 inches of soil on fertilized treatments as compared to the control treatment, and therefore do not include applied mineral nitrogen that moved below the surface 12 inches of soil). The Figures illustrate that $Ca(NO_3)_2$ as compared to $(NH_4)_2SO_4$ is first more subject to immobilization but then remineralizes rapidly toward the end of the season.

A comparison of nitrogen recovery in September from spring-applied $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ is shown in the bottom-half of Table 6. Two important differences between the recovery of fall and spring

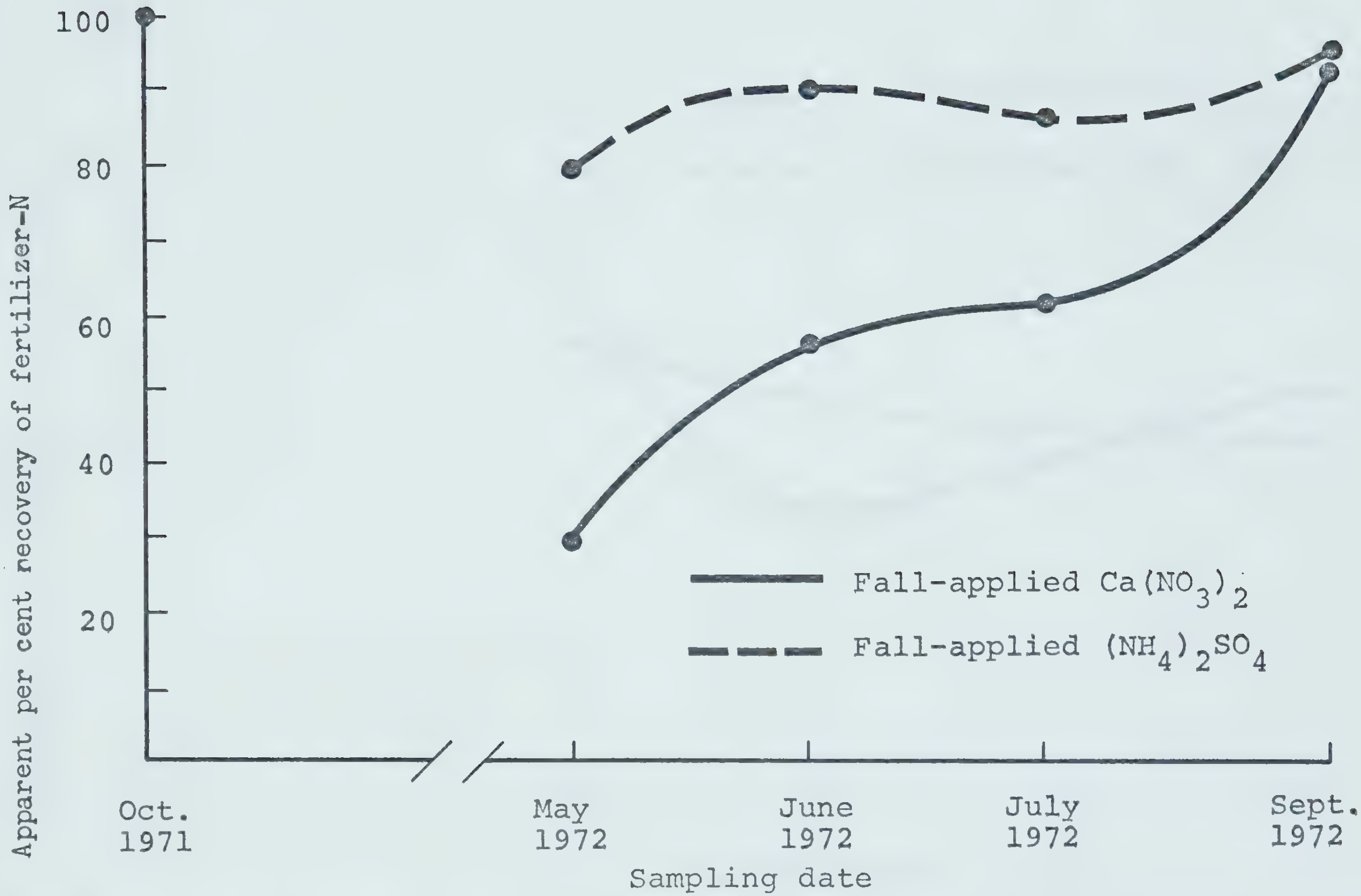

Figure 1. Recovery in non-cropped land of nitrogen fertilizers applied October, 1971 at Ellerslie (based on NH_4^+-N + NO_3^--N in top 12 inches of soil).

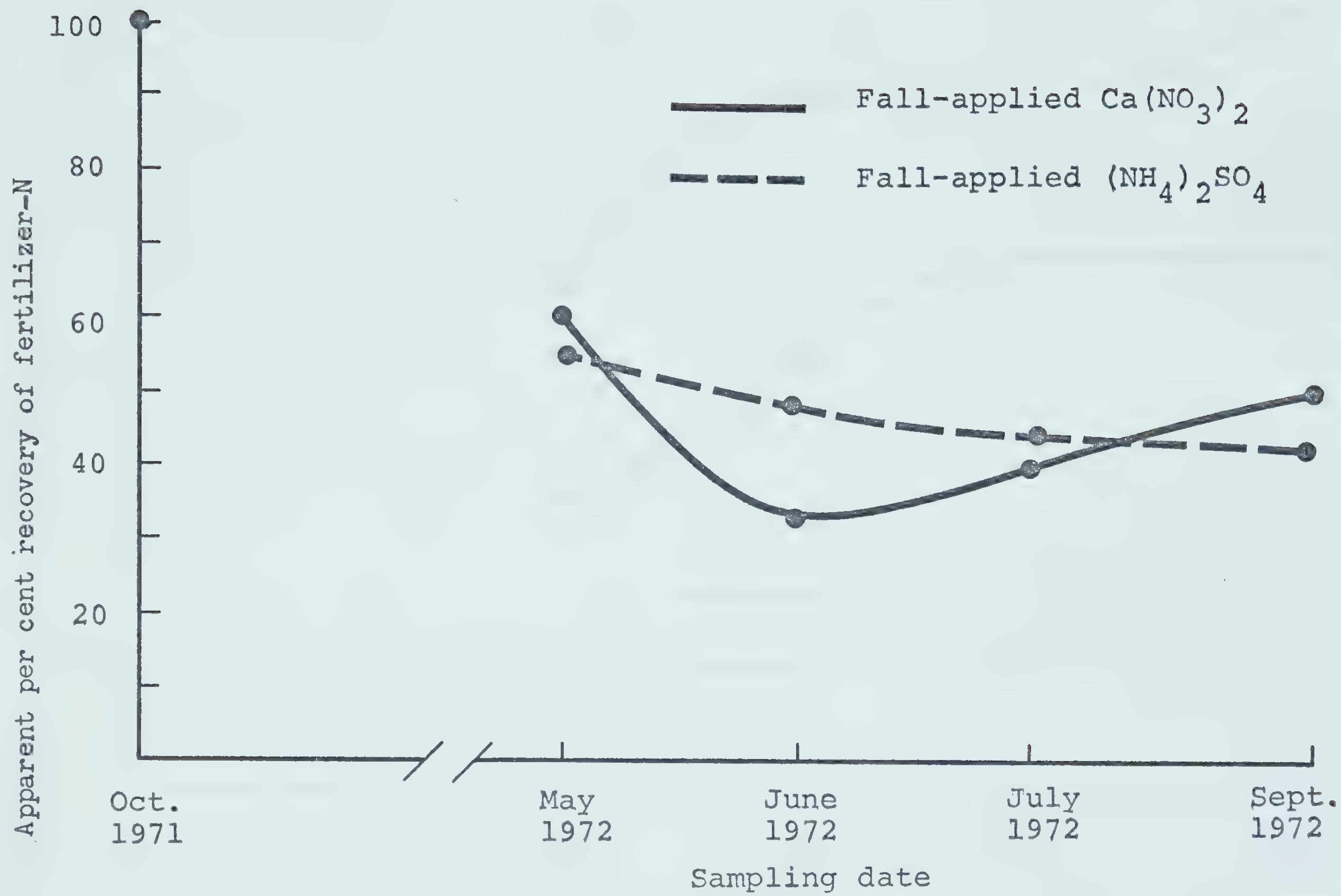

Figure 2. Recovery in non-cropped land of nitrogen fertilizers applied October, 1971 at Calmar (based on NH_4^+-N + NO_3^--N in top 12 inches of soil).

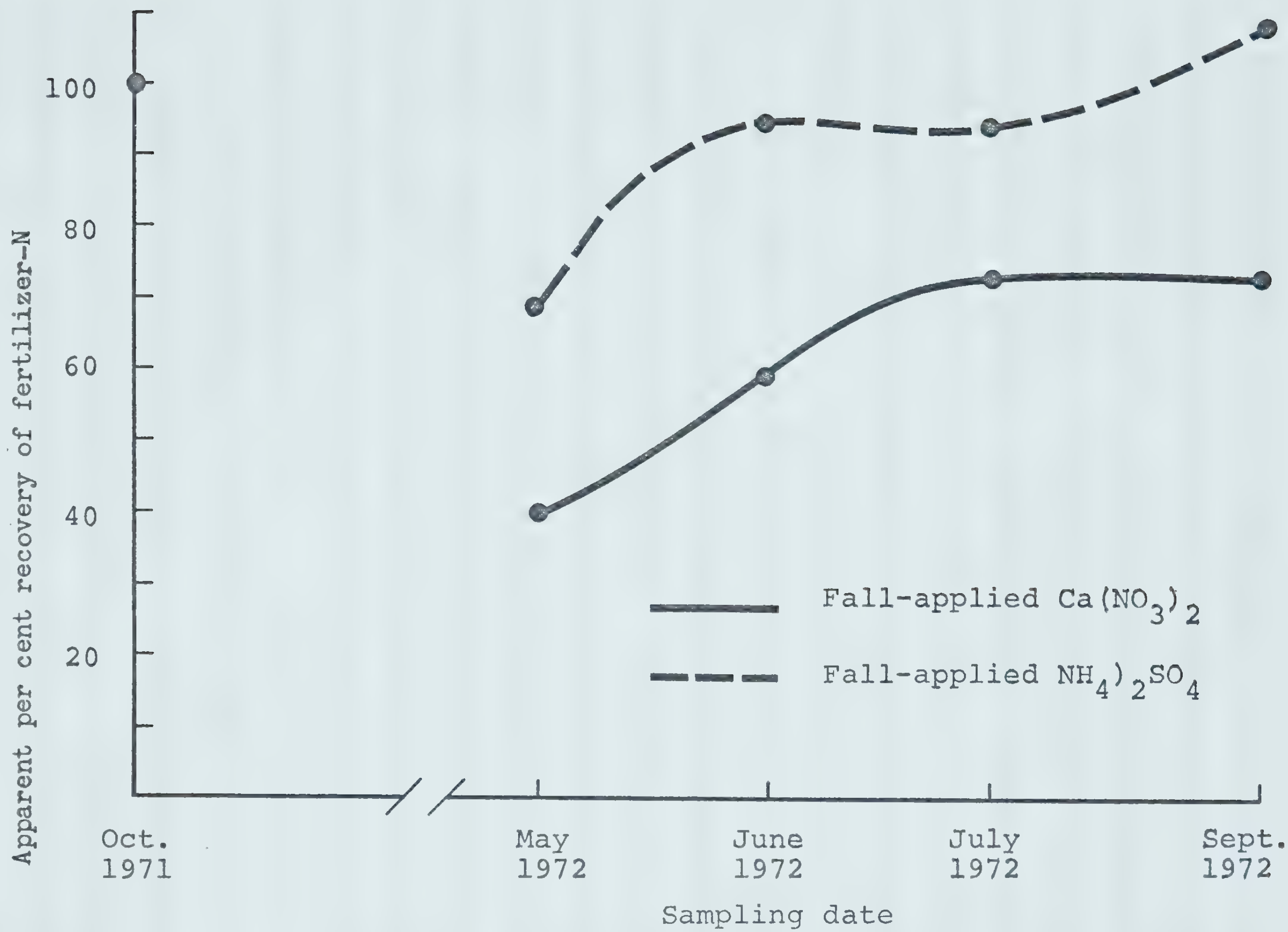

Figure 3. Recovery in non-cropped land of nitrogen fertilizers applied October, 1971 at Vilna (based on NH_4^+-N + NO_3^--N in top 12 inches of soil).

applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ were apparent: recovery of spring-applied $Ca(NO_3)_2$ was greater than recovery of fall-applied $Ca(NO_3)_2$; and recovery of spring-applied $Ca(NO_3)_2$ was greater than recovery of spring-applied $(NH_4)_2SO_4$. At the Ellerslie and Calmar sites,recovery of $(NH_4)_2SO_4$ was rather similar whether applied the previous fall or in the spring. However, at the Vilna site recovery of fall-applied $(NH_4)_2SO_4$ exceeded the recovery of spring-applied $(NH_4)_2SO_4$.

The apparent recovery in September of 184 per cent of spring-applied $Ca(NO_3)_2$ (Table 6) was evidence that the "priming effect" had occurred on this treatment at Ellerslie. The priming effect was also apparent at Vilna where 136 per cent of spring-applied $Ca(NO_3)_2$ was recovered in September. It is generally believed that the stimulating effect of fertilizer nitrogen on the release of native-soil nitrogen ("priming effect") occurs more readily with ammonium- than with nitrate-nitrogen (Broadbent, 1965), however the results at Ellerslie and Vilna support the opposite view.

When ammonium-based fertilizers are added to the soil they are rapidly oxidized by the nitrifying bacteria to nitrate-nitrogen. In order to delay nitrification of $(NH_4)_2SO_4$ in the field experiments, two methods were used: $(NH_4)_2SO_4$ was banded in the soil; and thiourea was added to the band of $(NH_4)_2SO_4$. The effect of these two methods on the nitrification of $(NH_4)_2SO_4$ at Ellerslie, Calmar and Vilna

is shown in Table 7. Five weeks after application most of the mixed $(NH_4)_2SO_4$ had undergone nitrification at all three field sites, whether applied the previous fall or in the spring. The almost complete nitrification of mixed ammonium is shown by the low ammonium-nitrogen content of those treatments and by the relatively high "apparent per cent of applied ammonium nitrified" (this later figure was calculated by expressing the increase in nitrate content of the top 12 inches of ammonium fertilized treatments as a percentage of the total amount of ammonium applied).

At all three sites, band application of ammonium greatly reduced the rate of nitrification of ammonium at 5 weeks after application. Banded ammonium, as compared to mixed ammonium (ammonium banded in the spring as compared to ammonium mixed in the spring) had at 5 weeks a higher ammonium content and a much lower "apparent per cent nitrification". On the basis of the "apparent per cent of applied ammonium nitrified" a reduction in nitrification lasted for at least 8 weeks at the Ellerslie site and for at least 16 weeks at the other two sites (Table 7).

Addition of thiourea to banded $(NH_4)_2SO_4$ further decreased nitrification (Table 7). At the Ellerslie site, addition of thiourea had an effect for at least 8 weeks as evidenced by increased ammonium-nitrogen content and decreased "apparent per cent of applied ammonium nitrified". Even after 16 weeks there was still some effect from addition of thiourea. Additional control over nitrification by adding thiourea to the band of $(NH_4)_2SO_4$ was also evident at the Calmar and Vilna sites, but the effect was not as great as at the Ellerslie site.

Table 7. Effects of band placement and addition of thiourea (50 lb. per acre) on nitrification of $(NH_4)_2SO_4$ in three non-cropped Alberta soils.

Site	Time of fertilizer application	Treatment	Method of application	Apparent recovery of NH_4^+-N (lb./acre) in top 12 inches of soil[1]			"Apparent per cent of applied ammonium nitrified"		
				5 weeks	8 weeks	16 weeks	5 weeks	8 weeks	16 weeks
Ellerslie	Fall	*$(NH_4)_2SO_4$	mixed	5	1	3	84	86	84
	Spring	*$(NH_4)_2SO_4$	mixed	10	9	1	67	84	90
		*$(NH_4)_2SO_4$	banded	25	5	4	26	41	72
		*$(NH_4)_2SO_4$ + thiourea	banded	54	24	10	14	21	40
Calmar	Fall	*$(NH_4)_2SO_4$	mixed	1	2	0	47	43	44
	Spring	*$(NH_4)_2SO_4$	mixed	10	4	0	51	44	50
		*$(NH_4)_2SO_4$	banded	9	5	10	2	0	13
		*$(NH_4)_2SO_4$ + thiourea	banded	21	13	12	0	0	8
Vilna	Fall	*$(NH_4)_2SO_4$	mixed	3	2	2	98	86	103
	Spring	*$(NH_4)_2SO_4$	mixed	10	11	0	72	89	91
		*$(NH_4)_2SO_4$	banded	30	19	0	21	29	20
		*$(NH_4)_2SO_4$ + thiourea	banded	30	32	2	23	18	11

* Fertilizers applied at a rate of 100 lb. N per acre

1 Calculated as the NH_4^+-N content of the fertilized treatment minus the NH_4^+-N content of the control treatment.

Results of Table 7 indicate that banding of $(NH_4)_2SO_4$, and especially addition of thiourea to banded $(NH_4)_2SO_4$ is effective in inhibiting nitrification of the majority of applied ammonium throughout most of the growing season. However, the results for banded $(NH_4)_2SO_4$ and for banded $(NH_4)_2SO_4$ plus thiourea may be somewhat inaccurate. For those two treatments the mineral nitrogen found in the soil accounted for only one-half or less of the applied ammonium at the Calmar and Vilna sites. It is possible that banded $(NH_4)_2SO_4$ may have been more subject to immobilization than mixed $(NH_4)_2SO_4$. More probable however, the low recovery of banded $(NH_4)_2SO_4$ was a relic of the sampling method used on the banded treatments. The banded treatments were sampled by taking separate 2-inch wide cores directly through the band of fertilizer and 2-inch wide cores exactly between the bands of fertilizer which were spaced 9 inches apart, and the amount of ammonium- and nitrate-nitrogen in pounds per acre was then calculated by assuming no transition zone of mineral nitrogen concentration. If the band of fertilizer was wider than the core taken, then the calculated amount of ammonium-nitrogen recovered and the "apparent per cent of applied ammonium nitrified" would be an under-estimate.

In view of the uncertainty of the calculation of ammonium- and nitrate-nitrogen in the banded treatments, another method of assessing the effect of thiourea on nitrification was used. The concentration of mineral nitrogen in the 2-inch wide core (6 inches deep) taken directly through the band of fertilizer was compared to the mineral nitrogen content of the similar core taken directly between the fertilizer

bands. Results are shown in Table 8 for sampling of banded treatments at 16 weeks, and there compared to unfertilized treatments and treatments receiving $(NH_4)_2SO_4$ mixed into the soil. At all three sites, ammonium content of bands of $(NH_4)_2SO_4$ were much higher than soil taken between the bands, or soil taken from treatments receiving mixed $(NH_4)_2SO_4$. In addition, $(NH_4)_2SO_4$ banded with thiourea contained two to three times as much ammonium as did the $(NH_4)_2SO_4$ banded without thiourea. These results demonstrate that band application of $(NH_4)_2SO_4$, and more so, the addition of thiourea to banded $(NH_4)_2SO_4$ to some degree reduced the rate of nitrification for at least 16 weeks.

The control over nitrification in the field experiments through band placement of $(NH_4)_2SO_4$ and addition of thiourea to the band of $(NH_4)_2SO_4$ confirms the earlier results obtained in the greenhouse. Banding of $(NH_4)_2SO_4$ was slightly more effective in inhibiting nitrification in the greenhouse than in the field. This would be expected because the rate of application of $(NH_4)_2SO_4$ in the greenhouse was approximately twice that used in the field, and with the higher salt concentration in the band the rate of nitrification would be less. When $(NH_4)_2SO_4$ was banded in the soil in the fall of the year at a rate of 100 lb. of nitrogen per acre at two field sites, Gasser (1965) recovered 10 ppm and 25 ppm of ammonium-nitrogen in the band the following spring (approximately 16 weeks later). Similar recovery of ammonium-nitrogen occurred in the present field experiments in which $(NH_4)_2SO_4$ was applied in the spring at time of seeding.

Other workers have demonstrated that thiourea inhibits

Table 8. Effects of band placement and addition of thiourea (50 lb. per acre) on nitrification of $(NH_4)_2SO_4$ after 16 weeks in three non-cropped Alberta soils.

Site	Time of fertilizer application	Treatment	Where sample taken	ppm N in top 6 inches of soil NH_4^+-N	NO_3^--N
Ellerslie	-	Control		2	33
	Fall	$(NH_4)_2SO_4$ mixed		3	84
	Spring	$(NH_4)_2SO_4$ mixed		3	82
		$(NH_4)_2SO_4$ banded	in band	14	99
			between band	3	79
		$(NH_4)_2SO_4$ + thiourea banded	in band	41	80
			between band	3	55
Calmar	-	Control		2	28
	Fall	$(NH_4)_2SO_4$ mixed		2	56
	Spring	$(NH_4)_2SO_4$ mixed		2	58
		$(NH_4)_2SO_4$ banded	in band	13	55
			between band	4	35
		$(NH_4)_2SO_4$ + thiourea banded	in band	24	49
			between band	4	29
Vilna	-	Control		5	30
	Fall	$(NH_4)_2SO_4$ mixed		6	84
	Spring	$(NH_4)_2SO_4$ mixed		4	82
		$(NH_4)_2SO_4$ banded	in band	21	56
			between band	3	32
		$(NH_4)_2SO_4$ + thiourea banded	in band	36	47
			between band	3	35

NOTE: For all treatments nitrogen applied at a rate of 100 lb. per acre.

nitrification when mixed in the soil (Hamlyn and Gasser, 1967; Fuller et al., 1950). However, the high rates of applications of thiourea required to inhibit nitrification when mixed in the soil may result in toxicity to plants. The greater control over nitrification when thiourea is banded with ammonium fertilizers than when mixed in the soil overcomes this problem of phytotoxicity.

Yield of Field Crops

At the Ellerslie site the growth of rape on the fall-applied $Ca(NO_3)_2$ treatment (Table 9) corresponded with the level of mineral nitrogen in the soil at different times of the growing season (Figure 1). In June, when the soil content of mineral nitrogen was low the growth of rape was also low. However, as nitrogen was remineralized later in the season the dry matter yield of rape increased and at harvest time in September there was no difference in the yield of rapeseed between the fall and the spring application of $Ca(NO_3)_2$. Fall-applied $(NH_4)_2SO_4$ was immobilized less than fall-applied $Ca(NO_3)_2$ which was apparent in the greater growth of rape on the fall-applied ammonium treatment in June. By September there was little difference in the yield of rapeseed from the two fall-applied fertilizers.

In July, the dry matter yield of rape was greater when $Ca(NO_3)_2$ was banded in the soil than when mixed, however by September there was little difference between these treatments in the yield of rapeseed. This preference for banded nitrate also occurred at the Vilna site. Band placement of $(NH_4)_2SO_4$ also resulted in better growth of rape in

Table 9. Growth of rape at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Yield of rape: Ellerslie June*	July*	Sept.+	Vilna Sept.+
--	Control	--	35a	105a	8.8a	13.3a
Fall	$Ca(NO_3)_2$	mixed	48ab	217b	16.4bc	18.6ab
	$(NH_4)_2SO_4$	mixed	75cd	246bc	13.9b	16.3a
Spring	$Ca(NO_3)_2$	mixed	67bcd	205b	16.2bc	20.8ab
	$Ca(NO_3)_2$	banded	57bc	333c	18.8bc	29.7c
Spring	$(NH_4)_2SO_4$	mixed	82d	276bc	16.3bc	14.7a
	$(NH_4)_2SO_4$	banded	70cd	333c	20.0c	19.2ab
	$(NH_4)_2SO_4$ + thiourea (50 lb./acre)	banded	49ab	224b	18.8bc	25.8bc

* Yields of dry matter in grams per portion of row.

+ Yields of rapeseed in cwt/acre.

NOTE: For each column values are significantly different (95% level of probability) when not followed by the same letter.

July than the mixed application of $(NH_4)_2SO_4$. Adding thiourea to the band of ammonium depressed the growth of rape in June and July at Ellerslie, but at harvest time in September the yield of rapeseed was as great as on the treatment which received ammonium alone. At the Vilna site, the yield of rapeseed was even slightly greater when thiourea was added to the band of ammonium.

The growth of oats was less responsive to the different times and methods of application of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ than was rape (Table 10). Fall applications of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ resulted in similar dry matter production of oats in June and July even though the level of mineral nitrogen was much less on the fall-applied nitrate treatment (Figure 1). By September the yield of oat forage was greater from fall-applied ammonium than from fall-applied nitrate. Apparently the remineralization of fall-applied nitrate did not supply sufficient nitrogen in the period from July to September, because it was at this time that growth of oats was depressed most on the fall-applied nitrate treatment. Spring applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ were equally effective in increasing the growth of oats throughout the season, and band placement of the fertilizers had no effect on the yield of oats compared to the mixed applications. Addition of thiourea to the band of ammonium slightly depressed the growth of oats early in the season at Ellerslie, however by September the yield of oat forage was the same as on the treatment in which ammonium was banded alone.

Barley grown at the Calmar site showed a somewhat different pattern of growth on the various nitrogen treatments than did oats

Table 10. Growth of oats at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Yield of oats: Ellerslie June*	Ellerslie July*	Ellerslie Sept.+	Vilna June*	Vilna July*	Vilna Sept.+
--	Control	--	25a	334a	58.1a	148a	557a	52.4a
Fall	$Ca(NO_3)_2$	mixed	30abc	424ab	73.3ab	166a	564a	54.5ab
	$(NH_4)_2SO_4$	mixed	32abc	458b	99.4b	151a	587a	76.1c
Spring	$Ca(NO_3)_2$	mixed	30abc	421ab	98.2b	138a	579a	67.0abc
	$Ca(NO_3)_2$	banded	29abc	409ab	99.8b	133a	558a	67.3abc
Spring	$(NH_4)_2SO_4$	mixed	36c	431ab	98.9b	134a	563a	70.7bc
	$(NH_4)_2SO_4$	banded	34bc	446b	102.7b	152a	545a	58.4ab
	$(NH_4)_2SO_4$+ thiourea (50 lb/acre)	banded	28ab	421ab	106.9b	148a	600a	69.0bc

* Yields of dry matter in grams per portion of row.

\+ Yields of oat forage in cwt/acre.

NOTE: For each column values are significantly different (95% level of probability) when not followed by the same letter.

and rape (Table 11). Like rape, the growth of barley was lower in June from fall-applied $Ca(NO_3)_2$ than from fall-applied $(NH_4)_2SO_4$. This difference was still apparent in July, however by September the yield of barley grain was only slightly lower from fall-applied nitrate than from fall-applied ammonium. Spring applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ were equally effective in increasing the midseason growth and the yield of barley grain. Band placement of ammonium and of nitrate depressed the growth of barley in June, but there was little difference between mixed and banded fertilizers in July and at harvest time in September. Addition of thiourea to the band of ammonium resulted in slightly lower dry matter production of barley in June and July. By September there was no longer any reduction in the yield of barley grain when thiourea was added to the band of ammonium.

The effect of different times and methods of application of ammonium- and nitrate-nitrogen on the mineral nitrogen content of the soil was reflected to some degree in the yield of field crops. Response of the three crops to the various treatments often varied because of preference for either ammonium- or nitrate-nitrogen, preference for banded and mixed applications of these nitrogen forms, and differences in the nitrogen requirements of each crop at different times during the growing season. Fall and spring applications of $(NH_4)_2SO_4$ were about equally effective in increasing the yield of all three field crops. At Rothamsted Experimental Station in Great Britain, Widdowson _et al_. (1961) found that spring-applied $(NH_4)_2SO_4$ gave a higher yield of winter wheat than $(NH_4)_2SO_4$ applied in autumn.

Table 11. Growth and nitrogen uptake of barley at different times of the growing season on nitrogen treatments at Calmar.

Time of fertilizer application	Treatment	Method of application	Yield of barley June*	Yield of barley July*	Yield of barley Sept.**	N-uptake of barley June+	N-uptake of barley July+	N-uptake of barley Sept.#
--	Control	--	27a	800a	8.6a	0.7a	1.2a	17.6a
Fall	$Ca(NO_3)_2$	mixed	58ab	1900ab	14.4ab	2.5ab	5.7bc	36.6ab
	$(NH_4)_2SO_4$	mixed	104cde	3600c	18.6bc	2.8abc	4.6b	33.7ab
Spring	$Ca(NO_3)_2$	mixed	112de	3600c	24.8cd	5.2d	8.9c	60.1d
	$Ca(NO_3)_2$	banded	70bc	3700c	26.8d	5.1d	8.9c	58.4d
Spring	$(NH_4)_2SO_4$	mixed	136e	3600c	24.2cd	4.0bcd	5.3b	49.0bcd
	$(NH_4)_2SO_4$	banded	81bcd	3400bc	28.0d	3.5bcd	7.3bc	57.8cd
	$(NH_4)_2SO_4$ + thiourea (50 lb/acre)	banded	70bc	2600bc	27.6d	2.2ab	5.7bc	58.6d

\+ Nitrogen uptake in grams of nitrogen per portion of row.

\# Nitrogen uptake in pounds of nitrogen per acre.

* Yields of dry matter in grams per portion of row.

** Yields of barley grain in cwt/acre.

NOTE: For each column values are significantly different (95% level of probability when not followed by the same letter).

The similar crop yields from spring and fall applications of $(NH_4)_2SO_4$ in the present field experiments may be attributable to the low levels of rainfall and the cold winters in central Alberta, which would limit the nitrification of fall-applied $(NH_4)_2SO_4$ and the subsequent leaching of nitrate-nitrogen from the upper soil horizons. Fall application of $Ca(NO_3)_2$ generally resulted in lower yields of oats and barley than did the spring application of $Ca(NO_3)_2$. Early season growth of rape was also low with fall-applied $Ca(NO_3)_2$, however in September the yield of rapeseed was similar whether $Ca(NO_3)_2$ was applied in the fall or in the spring. This pattern of growth of rape on the fall-applied $Ca(NO_3)_2$ treatment corresponded with the level of mineral nitrogen in the soil at different times during the growing season.

There was little difference in the yield of oats or barley when the nitrogen fertilizers were mixed and when banded in the soil, but the growth of rape was generally greater when these fertilizers were banded in the soil. The preference of rape for banded $Ca(NO_3)_2$ is surprising because one would expect $Ca(NO_3)_2$ to diffuse from the band soon after placement of the fertilizer in the soil. A possible explanation for the better growth of rape when $Ca(NO_3)_2$ was banded than when mixed in the soil is that less nitrate-nitrogen would be immobilized when placed in a band, thereby increasing the availability of nitrate-nitrogen for plant growth.

Addition of thiourea to the band of $(NH_4)_2SO_4$ depressed the growth of all crops early in the season, however there were no visible signs of toxicity of thiourea to the plants at the rate of thiourea used in these field experiments (50 lb. per acre). While thiourea did

reduce the rate of nitrification of $(NH_4)_2SO_4$ there was not an increase in the yield of oats or barley associated with the use of thiourea. In western Canada one would not expect thiourea to increase crop yields when applied in the spring, because the amount of nitrate-nitrogen lost through leaching is normally very low during the summer. Thiourea might be of considerably greater value when applied in the fall of year. By preventing nitrification of fall-applied ammonium fertilizers there would be less chance of nitrogen loss through leaching of nitrate-nitrogen in the fall and early in the spring.

Nitrogen Uptake of Field Crops

The low mineral nitrogen content of soil in the non-cropped portion of treatments at Calmar (Table 6) was reflected in the low uptake of nitrogen by barley at this site as shown in Table 11. On the spring-applied nitrogen treatments barley took up approximately 55 pounds of nitrogen per acre by September, whereas rape and oats grown at the other field sites often contained more than 100 pounds of nitrogen per acre. When $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ were applied in the fall of the year at Calmar, barley took up less nitrogen than when these fertilizers were applied in the spring at time of seeding. There was little difference in nitrogen uptake of barley on treatments which received fall applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$, however when applied in spring, the uptake of nitrogen was slightly greater from $Ca(NO_3)_2$ than from $(NH_4)_2SO_4$. Banding of $Ca(NO_3)_2$ had little effect on the nitrogen uptake of barley, but when $(NH_4)_2SO_4$ was banded rather

than mixed in the soil the uptake of nitrogen was slightly increased. Adding thiourea to the band of $(NH_4)_2SO_4$ depressed the uptake of nitrogen by barley in June. By September, barley had taken up as much nitrogen on the treatment which received thiourea as on the banded $(NH_4)_2SO_4$ treatment.

The effect of the various times and methods of application of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ on the nitrate-nitrogen content of barley is shown in Table 12. In June, barley grown on treatments which received $Ca(NO_3)_2$ contained the highest concentration of nitrate-nitrogen (approximately 0.50% NO_3^--N). When $Ca(NO_3)_2$ was applied in the fall of the year there was 0.30 per cent nitrate-nitrogen in barley. Thiourea had little effect in reducing the accumulation of nitrate-nitrogen below that of barley which received $(NH_4)_2SO_4$ alone. The per cent nitrate-nitrogen in barley straw in September was very low for all treatments (approximately 0.01% NO_3^--N).

Differences in the nitrogen uptake of oats between the various treatments were generally less pronounced than for rape and barley (Table 13). Spring applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ were equally effective in increasing the nitrogen content of oats. However, when these fertilizers were applied in the fall of the year the nitrogen uptake of oats was greater with $(NH_4)_2SO_4$ than with $Ca(NO_3)_2$. There was no difference in the nitrogen uptake of oats when $Ca(NO_3)_2$ was banded and when mixed in the soil, but banding of $(NH_4)_2SO_4$ depressed nitrogen uptake slightly. Adding thiourea to the band of $(NH_4)_2SO_4$ did not decrease the nitrogen uptake of oat forage.

In June, oats accumulated high levels of nitrate-nitrogen

Table 12. Per cent nitrate-nitrogen in barley at different times of the growing season on nitrogen treatments at Calmar.

Time of fertilizer application	Treatment	Method of application	Per cent nitrate-nitrogen in barley		
			June	July	Sept.+
--	Control	--	0.11ab*	0a	0a
Fall	$Ca(NO_3)_2$	mixed	0.30bc	0.23d	0.05b
	$(NH_4)_2SO_4$	mixed	0.05a	0a	0a
Spring	$Ca(NO_3)_2$	mixed	0.48c	0.14c	0.01a
	$Ca(NO_3)_2$	banded	0.49c	0.08bc	0.01a
Spring	$(NH_4)_2SO_4$	mixed	0.11ab	0a	0.01a
	$(NH_4)_2SO_4$	banded	0.24ab	0.02ab	0.01a
	$(NH_4)_2SO_4$+ thiourea (50 lb/acre)	banded	0.04a	0.02ab	0.01a

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

\+ Per cent nitrate-nitrogen in barley straw.

Table 13. Nitrogen uptake of oats at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Nitrogen uptake of oats: Ellerslie June*	Ellerslie July*	Ellerslie Sept.+	Vilna June*	Vilna July*	Vilna Sept.+
--	Control	--	1.5a	5.5a	48.9a	4.6a	9.3a	40.7a
Fall	$Ca(NO_3)_2$	mixed	2.0abc	12.9bcd	96.1b	6.8a	12.5abc	70.9ab
	$(NH_4)_2SO_4$	mixed	2.1bcd	15.3d	134.6b	7.3a	16.7cd	124.4c
Spring	$Ca(NO_3)_2$	mixed	2.0bcd	14.1cd	124.7b	6.6a	16.2bcd	115.8c
	$Ca(NO_3)_2$	banded	1.9abc	13.5bcd	123.6b	6.2a	16.2bcd	107.8c
Spring	$(NH_4)_2SO_4$	mixed	2.5d	13.7bcd	126.5b	6.6a	17.6d	112.5c
	$(NH_4)_2SO_4$	banded	2.3cd	13.0bcd	104.1b	6.6a	16.2bcd	92.7bc
	$(NH_4)_2SO_4$+ thiourea (50 lb/acre)	banded	1.9abc	11.3bc	101.5b	6.1a	15.4bcd	94.0bc

* Nitrogen uptake in grams of nitrogen per portion of row.

\+ Nitrogen uptake in pounds of nitrogen per acre.

NOTE: For each column values are significantly different (95% level of probability) when not followed by the same letter.

(approximately 1% NO_3^--N), however as the plant matured the concentration of nitrate-nitrogen decreased (Table 14). Crawford et al. (1961) have attributed this decrease in concentration of nitrate-nitrogen with maturity to a dilution in the concentration of nitrate-nitrogen from increased yield of oats. They also found that band placement of NH_4NO_3 had no effect on the concentration of nitrate-nitrogen in timothy hay when compared to a broadcast application. In the present field experiments, banded and mixed applications of $Ca(NO_3)_2$ resulted in similar concentrations of nitrate-nitrogen in oats, however banding of $(NH_4)_2SO_4$ slightly reduced the concentration of nitrate-nitrogen in oats, and adding thiourea to the band of $(NH_4)_2SO_4$ further decreased nitrate accumulation. Fall-applied $Ca(NO_3)_2$ generally resulted in a lower concentration of nitrate-nitrogen in oats than the spring application of $Ca(NO_3)_2$, whereas fall and spring applications of $(NH_4)_2SO_4$ differed very little in the concentration of nitrate-nitrogen in oats.

The uptake of nitrogen by rape grown at Ellerslie and Vilna is shown in Table 15. In most, but not all cases the nitrogen uptake of rape was similar at both sites. Rape contained less nitrogen when $Ca(NO_3)_2$ was applied in the fall of the year than when applied in spring. The lower uptake of nitrogen in September from fall-applied $Ca(NO_3)_2$ than from fall-applied $(NH_4)_2SO_4$ was evidence that the remineralization of $Ca(NO_3)_2$ during the summer (Figure 1) was not adequate for maximum uptake of nitrogen by rape. Fall and spring

Table 14. Per cent nitrate-nitrogen in oats at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Per cent nitrate-nitrogen in oats: Ellerslie			Vilna		
			June	July	Sept.	June	July	Sept.
--	Control	--	0.77a*	0.02a	0a	0.14a	0.03a	0a
Fall	$Ca(NO_3)_2$	mixed	0.86ab	0.35cde	0.13b	0.45a	0.15b	0.07abcd
	$(NH_4)_2SO_4$	mixed	0.01c	0.51e	0.11ab	0.70a	0.27cd	0.20de
Spring	$Ca(NO_3)_2$	mixed	1.01c	0.47de	0.05ab	0.75a	0.29cd	0.22e
	$Ca(NO_3)_2$	banded	0.99c	0.45cde	0.05ab	0.65a	0.31cd	0.17bcde
Spring	$(NH_4)_2SO_4$	mixed	1.01c	0.43cde	0.13b	0.74a	0.36d	0.18cde
	$(NH_4)_2SO_4$	banded	0.91bc	0.28abc	0.04ab	0.49a	0.27cd	0.13abcde
	$(NH_4)_2SO_4$+ thiourea (50 lb/acre)	banded	0.81ab	0.15ab	0.01ab	0.36a	0.14b	0.05abc

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

Table 15. Nitrogen uptake of rape at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Nitrogen uptake of rape: Ellerslie June*	Ellerslie July*	Ellerslie Sept.+	Vilna Sept.+
--	Control	--	1.0a	1.2a	34.0a	75.2a
Fall	$Ca(NO_3)_2$	mixed	2.1ab	3.6b	80.4b	110.5ab
	$(NH_4)_2SO_4$	mixed	4.1d	4.6bc	119.1bc	96.1ab
Spring	$Ca(NO_3)_2$	mixed	4.0d	3.9b	118.5bc	154.3bc
	$Ca(NO_3)_2$	banded	3.9cd	7.3cd	117.2bc	195.5c
Spring	$(NH_4)_2SO_4$	mixed	4.4d	5.1bc	105.0bc	125.3ab
	$(NH_4)_2SO_4$	banded	4.2d	7.9d	133.8c	120.3ab
	$(NH_4)_2SO_4$+ thiourea (50 lb/acre)	banded	2.6bc	4.2b	116.7bc	147.3bc

* Nitrogen uptake in grams of nitrogen per portion of row.

\+ Nitrogen uptake in pounds of nitrogen per acre.

NOTE: For each column values are significantly different (95% level of probability) when not followed by the same letter.

applications of $(NH_4)_2SO_4$ were about equally effective in increasing the nitrogen uptake of rape. Band placement of both $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ resulted in greater uptake of nitrogen in July than the mixed application of these fertilizers, however by September differences were smaller.

The pattern of nitrogen uptake of rape on the treatment which received thiourea corresponded with the nitrification of $(NH_4)_2SO_4$ on this treatment (Table 7). In June and July when nitrification of $(NH_4)_2SO_4$ was low the uptake of nitrogen was also low, but by September, when nitrification was complete, rape had taken up as much nitrogen as rape grown on the treatment which received $(NH_4)_2SO_4$ alone.

The accumulation of nitrate-nitrogen in rape at the Ellerslie and Vilna sites is shown in Table 16. The low recovery of mineral nitrogen in late May from the fall application of $Ca(NO_3)_2$ (Table 5) was evident in the low concentration of nitrate-nitrogen in rape grown on this treatment (0.29% NO_3^--N). Five weeks after the spring application of $Ca(NO_3)_2$ (June), rape contained 1.30 per cent nitrate-nitrogen, whereas rape that received $(NH_4)_2SO_4$ contained 0.86 per cent nitrate-nitrogen. These levels of nitrate accumulation in rape are generally higher than values reported in the literature. For example, Griffith and Johnston (1960) found that rape contained only 0.37 per cent nitrate-nitrogen at four weeks after application of $(NH_4)_2SO_4$ (rate of application of N was 60 lb. per acre). In addition, these authors reported that there was no difference between ammonium- and nitrate-containing fertilizers in the level of nitrate accumulation in rape.

Table 16. Per cent nitrate-nitrogen in rape at different times of the growing season on nitrogen treatments at Ellerslie and Vilna.

Time of fertilizer application	Treatment	Method of application	Per cent nitrate-nitrogen in rape: Ellerslie June	Ellerslie July	Ellerslie Sept.+	Vilna Sept.+
--	Control	--	0.03a*	0.01a	0.01a	0.03a
Fall	$Ca(NO_3)_2$	mixed	0.29ab	0.05ab	0.05ab	0.05a
	$(NH_4)_2SO_4$	mixed	1.05de	0.21bcde	0.29d	0.13a
Spring	$Ca(NO_3)_2$	mixed	1.30e	0.12abcd	0.23cd	0.25a
	$Ca(NO_3)_2$	banded	1.71f	0.29e	0.17bcd	0.21a
Spring	$(NH_4)_2SO_4$	mixed	0.86cd	0.22cde	0.12abc	0.23a
	$(NH_4)_2SO_4$	banded	0.65bcd	0.26de	0.17bcd	0.04a
	$(NH_4)_2SO_4$ + thiourea (50 lb/acre)	banded	0.31ab	0.09abc	0.07ab	0.02a

* For each column values are significantly different (95% level of probability) when not followed by the same letter.

\+ Per cent nitrate-nitrogen in rape straw.

The results of the present experiments indicate that nitrate accumulation is greater, at least in the early stages of growth, when rape is fertilized with $Ca(NO_3)_2$ rather than with $(NH_4)_2SO_4$. It is also evident that method of application of $Ca(NO_3)_2$ can be an important factor in nitrate-accumulation of rape, because rape which received the banded application of $Ca(NO_3)_2$ accumulated significantly more nitrate-nitrogen than rape grown on the mixed $Ca(NO_3)_2$ treatment. Banding of $(NH_4)_2SO_4$ had little effect on the concentration of nitrate-nitrogen in rape compared to mixed $(NH_4)_2SO_4$, however when thiourea was added to the band of $(NH_4)_2SO_4$ the concentration of nitrate-nitrogen in rape was reduced, particularly in the early stages of growth.

Nitrogen fertilizers applied in the fall of the year have generally been found to be less effective in increasing the nitrogen uptake of field crops than when the fertilizers are applied in the spring at time of seeding. For example, in Great Britain, Devine and Holmes (1964) found that winter wheat took up less nitrogen when $(NH_4)_2SO_4$ and $Ca(NO_3)_2$ were applied in the fall than when applied in the spring, which they attributed to the loss of nitrogen through leaching of the fall-applied fertilizers. In the present field experiments, fall application of $(NH_4)_2SO_4$ was found to result in nitrogen uptake of rape and oats as great as that from spring-applied $(NH_4)_2SO_4$. $Ca(NO_3)_2$, on the other hand was generally less efficient when applied in the fall. At the Ellerslie site, the low uptake of nitrogen by rape in June from fall-applied $Ca(NO_3)_2$ was not because of over winter leaching of nitrate-nitrogen, but rather because the fertilizer was immobilized in the

spring. The subsequent remineralization of nitrogen during the growing season was not as effective in increasing the nitrogen uptake of rape as was spring-applied $Ca(NO_3)_2$.

The pattern of nitrogen uptake of rape was different when $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ were banded and when mixed in the soil, but nevertheless there was little difference in the total uptake of nitrogen in September. The effect of band placement of the fertilizers was to increase the rate of nitrogen uptake of rape compared to the broadcast application. Adding thiourea to the band of $(NH_4)_2SO_4$ depressed the uptake of nitrogen of all crops early in the season, however by harvest time in September the total uptake of nitrogen was as great as on the treatment which received $(NH_4)_2SO_4$ alone. Beaton *et al*. (1967) showed that nitrogen uptake of orchardgrass was increased slightly when thiourea was added to urea (2:8 mixture), but there was no evidence of a reduced rate of nitrogen uptake of orchardgrass when thiourea was used.

In the present experiments, thiourea was found to reduce the level of nitrate-nitrogen accumulation in the field crops, often from potentially toxic levels to levels considered safe for cattle consuming the plants. For example, at the Ellerslie site, oats which received the mixed applications of $(NH_4)_2SO_4$ contained 0.43 per cent nitrate-nitrogen in July (heading) which is above the maximum safe level of 0.20 per cent nitrate-nitrogen in cattle forage (Bradley *et al*. 1940). However, when thiourea was banded with $(NH_4)_2SO_4$ there was only 0.15 per cent nitrate-nitrogen in oats, which could be safely fed to cattle.

SUMMARY AND CONCLUSIONS

The literature generally supports the view that there is little difference in the yield of different crops fertilized with nitrate and with ammonium, because in most instances applied ammonium is rapidly nitrified in the soil to nitrate-nitrogen. However, when soils do not nitrify rapidly,response of plants may be quite different to applications of ammonium as compared to nitrate. In the present study, for example, radish and spinach grown in pot culture on a slowly nitrifying soil showed a marked response to the form of applied nitrogen, expecially at very high rates of application (200 and 400 ppm N). The response was a reduction in plant growth with ammonium as opposed to nitrate, due to the toxicity to plants of high concentrations of ammonium.

The toxicity of ammonium demonstrated in pot culture was not apparent in field experiments with barley, oats and rape which received a more moderate rate of ammonium-nitrogen (100 lb. per acre). In fact, under field conditions it may be of advantage to retain fertilizer nitrogen in the ammonium form, provided rates of fertilizer application are not so high that crops would suffer from toxicity of ammonium. The advantage of retaining nitrogen in the ammonium form is that ammonium is much less susceptible than nitrate to both leaching and denitrification. A portion of the work in the present study was devoted to finding a practical way of inhibiting nitrification of ammonium-based fertilizers. The main purpose of the present study was to determine

the effect of applied ammonium- and nitrate-nitrogen on crops, but a practical way of inhibiting nitrification of applied ammonium was necessary to the study.

Greenhouse experiments showed that nitrification of $(NH_4)_2SO_4$ and urea could be reduced through band placement of these fertilizers and further reduced by adding low rates of thiourea (less than 40 ppm) to the band of ammonium. When thiourea was applied in a band with the fertilizer, the problem of its phytotoxicity (Fuller et al., 1950) was avoided because only light rates of thiourea were required to inhibit nitrification. Thiourea was not toxic to barley or radish in the greenhouse when applied at a rate of 20 or 25 ppm, nor toxic to barley, oats and rape in the field at a rate of 50 lb. per acre. The 50-lb. rate of thiourea placed in a band with $(NH_4)_2SO_4$ reduced nitrification throughout the growing season in three field experiments.

Growth of rape, uptake of nitrogen and nitrate accumulation were all depressed early in the season by addition of thiourea in the field experiments. These findings agree with work by Nyborg (personal communication) who found that rape required nitrate-nitrogen in its early stages of growth. In the present experiments, the effect of thiourea on rape was no longer evident at harvest time. Oats absorbed ammonium as readily as nitrate and addition of thiourea to banded $(NH_4)_2SO_4$ had little effect on the growth and nitrogen uptake of oats.

Method of application of fertilizer (i.e. mixing or band placement) influenced the yield of rape. Banded application of $Ca(NO_3)_2$ and of $(NH_4)_2SO_4$ produced greater growth and nitrogen uptake of rape at mid-season (July) than did the mixed application of these fertilizers. Accompanying the greater uptake of nitrogen on the banded-nitrate treatment was an increase in the accumulation of nitrate-nitrogen in rape. At harvest time this preference for banded nitrogen was less apparent. Unlike rape, oats and barley were unaffected by the method of application of $(NH_4)_2SO_4$ and $Ca(NO_3)_2$. Apart from the preference of rape for nitrate there was no evidence of ammonium toxicity to plants at rates of ammonium used in the greenhouse experiments (100 ppm NH_4^+-N) or in the field experiments (100 lb. per acre of NH_4^+-N).

Included in the field experiments were comparisons of fall and spring applications of $Ca(NO_3)_2$ and $(NH_4)_2SO_4$ for spring-sown crops. Generally, fall and spring applications of $(NH_4)_2SO_4$ were equally effective in increasing the nitrogen uptake and growth of field crops, while $Ca(NO_3)_2$ applied in the fall of the year was, in most cases less efficient than spring-applied nitrate. For rape, this inferiority of fall-applied nitrate was particularly apparent early in the season due to the immobilization of the fertilizer, and the high demand for nitrate-nitrogen by rape at this time. Lower uptake of nitrogen by oats from fall-applied nitrate was evident later in the season when this crop took up most of its nitrogen.

Results of this study show that the effect of nitrogen fertilizers on the nitrogen uptake and yield of crops may be substantially

influenced by the form of applied nitrogen and the time and method of fertilizer application, as well as by the addition of a nitrification inhibitor. Specific findings of this work are:

1. Differences in the growth and nitrogen uptake of field crops grown following fall fertilization with $Ca(NO_3)_2$ as compared to $(NH_4)_2SO_4$ appear to be the result of the different patterns of immobilization and remineralization of the two fertilizers. Fall-applied nitrate is immobilized more quickly and to a greater degree than fall-applied ammonium. Both forms are apparently remineralized during the following season, but nitrate is remineralized later in the season. The immobilization of fall-applied nitrate resulted in reduced growth and nitrogen uptake of rape early in the season. Reduction in the growth and nitrogen uptake of oats from fall-applied $Ca(NO_3)_2$ as compared to fall-applied $(NH_4)_2SO_4$ was not evident until later in the season.
2. Fall and spring applications of $(NH_4)_2SO_4$ were equally effective in increasing the yield and nitrogen uptake of rapeseed, barley grain, and oat forage. However, fall application of $Ca(NO_3)_2$ gave less growth and nitrogen uptake in barley than did spring application of $Ca(NO_3)_2$. Oat forage took up less nitrogen when $Ca(NO_3)_2$ was applied in the fall as compared to the spring, but there was little difference in the yield.
3. There was an apparent preference of rape for nitrogen fertilizers which were placed in a band rather than when mixed in the soil, but oats and barley were not affected by the method of fertilizer

application. Also indicated was a greater preference of rape for nitrate- than for ammonium-nitrogen.

4. Thiourea was effective in inhibiting nitrification of ammonium when placed in a band with $(NH_4)_2SO_4$. At the rate of thiourea used in the field experiments (50 lb. per acre) there was no evidence of toxicity of thiourea to the crops studied. The effect of thiourea was to modify the growth and nitrogen-uptake pattern or rape, and to decrease the mid-season accumulation of nitrate-nitrogen in rape and oats. One aspect which was not covered in the present study was the use of thiourea in preventing the over-winter loss of fall-applied ammonium through leaching and denitrification of nitrate-nitrogen. Further experimentation and evaluation under such conditions are necessary to ascertain the full potential of thiourea in the production of field crops.

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APPENDIX I

Legal location and description of soils used for field experiments.

Site	Legal Location	Initial nitrogen content (ppm)* NH_4^+-N	NO_3^--N	Texture*	pH*	Organic matter (%)*
Ellerslie	NE-6-51-24-W4	4	10	SiCL	6.2	12.5
Calmar	SW-4-49-27-W4	2	1	CL	6.4	11.3
Vilna	NW-15-59-12-W4	5	4	SL	6.1	5.0

* Surface 6 inches of soil.

APPENDIX II

Nitrogen fertilizers used in greenhouse and field experiments.

Chemical name	Chemical formula	Solubility in water (g/100 ml.)
ammonium chloride	NH_4Cl	29.4 @ 0°C
ammonium sulfate	$(NH_4)_2SO_4$	70.6 @ 0°C
calcium nitrate	$Ca(NO_3)_2$	50.5 @ 0°C
sodium nitrate	$NaNO_3$	73.0 @ 0°C
urea	NH_2CONH_2	78.0 @ 5°C
thiourea	NH_2CSNH_2	9.18 @ 13°C

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